From working memory to maths: A multi-measure physiological investigation of the impact of anxiety

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Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 65,000 words including appendices, bibliography, footnotes, tables and equations and has fewer than 150 figures.

Chiara Avancini
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Al mio papà, la cui memoria mi ha dato la forza di andare avanti quando pensavo che non ce l'avrei fatta. So che saresti fiero di me.
E alla mia mamma. Esempio di forza, determinazione ed intelligenza.

To my father, whose memory gave me the strength to carry on when I thought I could not. I know you would be proud of me.
And to my mother. Woman of strength, determination and intelligence.

Truth about Giulio Regeni

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dad, whom I miss dearly and that would be so proud of me. I wish you were here reading these words and sharing these moments with me.

Abstract

From working memory to maths: A multi-measure physiological investigation of the impact of anxiety

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The present research project adopted physiological measures to investigate the relationship between anxiety and working memory (WM). The importance of WM for maths processing and the sensitivity of physiological measures to both anxious responses and executive processes make these measures appealing for advancing our understanding of maths anxiety (MA). The overarching research question asked whether anxiety affects the accuracy of the representations in WM, process that is thought to be central in performing maths task and that may explain the relationship between maths performance and MA.

In this thesis the construct of anxiety was considered under two aspects. First, as source of noise causing a decrease in performance to tasks relying on WM. Second, as evolutionary determined physiological reaction to stressors. The former conceptualization of anxiety informed the parts of this thesis investigating the effects of anxiety over WM. The latter provided the starting point to investigate how physiological measures may provide insights on the relationship between the effects of MA on WM processes and maths performance.

The first two studies in the thesis aimed at addressing the question of whether anxiety affects WM. WM was conceptualized as a limited capacity system where information is temporarily maintained and manipulated in order to perform a task. It is necessary for performing complex cognitive tasks as well as for later encoding of information in long term memory (Baddeley, 1992). The efficiency of such system can be compromised by events external or internal to the individual. One factor that may impact WM efficiency is anxiety. Anxiety is a state of tension in the face of threat and it is characterised by worry and increased physiological arousal. Task-irrelevant self-directed thoughts might reduce WM resources otherwise needed for performing cognitive tasks (Eysenck et al., 2007). Moreover, the effect that anxiety has on maths performance, as in the case of maths anxiety (MA), might be

explained by the effect of anxiety on WM processing (Ashcraft and Kirk, 2001). The present thesis investigates the interplay between these three constructs with the aid of physiological measures.

Attentional control has been found to be a central function of WM processing (Baddeley, 1992; Eysenck, 2007). In the first experiment I look at the involvement of attentional processes in memory encoding by investigating whether ERP prestimulus-memory effects (pSMEs) are of attentive nature (Otten et al., 2006). If that was the case, investigating how anxiety affected attentional processed prior memory encoding would have provided a starting point to address how MA may exert its influence on the performance of maths tasks. Contrary to my prediction, the pSME seemed to be better explained by semantic processing, rather than recruitment of attentional processes.

In the second experiment, I investigated how anxiety affects maintenance in WM. To this aim I used experimentally induced by threat-of-shock might impact WM as conceptualized by resource models. Resource models of WM give a central role to attentional resources (Ma et al, 2014). To do so I implemented a modified NPU-threat test protocol (Shmitz & Grillon, 2012) combined with task in which WM was assessed through precision of recall (Bays et al., 2009) and anxiety was assessed by means of the startle reflex. In the different conditions, the probability of receiving a shock was manipulated and the estimates of the distributions fitted to the data were compared to assess whether anxiety decreased precision of recall.

In a third experiment I looked at the specific case of MA. It is thought that MA impairs maths performance by depleting WM resources (Ashcraft and Kirk, 2001). While MA impacts on implicit processes such as WM, very few studies have attempted to investigate implicit measures of MA with varying success. In the experiment I attempt to replicate the behavioural findings of Rubinsten et al. (2010 and 2012) in which they use an affective priming task combined with a verification task. Furthermore, I investigate the startle reflex and heart rate variability as implicit physiological measures, which have never been studied in the context of MA.

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Nomenclature

ACT Attentional Control Theory

AIC Akaike Information Criterion

AMAS Abbreviated Maths Anxiety Scale

ANOVA Analysis of Variance

ANS Autonomic Nervous System

ATMS Anxiety Towards Mathematics Scale

BANOVA Bayesian Analysis of Variance

BF Bayesian Factor

CE Central Executive

DD Developmental Dyscalculia

ECG Electrocardiogram

EEG Electroencephalography

EMG Electromyography

ERP Event-Related brain Potential

HF High Frequencies

HMA High Maths Anxious

HPA Hypothalamus-Pituitary-Adrenal axis

HR Heart Rate

HRV Heart Rate Variability

IBIs Inter-Beat-Intervals

LF Low Frequencies

LMA Low Maths Anxious

LTM Long Term Memory

LTS Long Term Store

MA Maths Anxiety

MARS Mathematics Anxiety Rating Scale

MAS Mathematics Anxiety Scale

MLE Maximum Likelihood Estimation

MMA Medium Maths Anxious

PFC Prefrontal Cortex

PTSD Post-Traumatic Stress Disorder

RMSSD Root Mean Square of Successive Differences between normal heartbeats

RTs Reaction Times

SD Standard Deviation

SDNN Standard Deviation of Normal to Normal sinus beats

STS Short Term Store

TF Time-Frequency

VSWM Visuospatial Working Memory

WM Working Memory

dlPFC dorsolateral Prefrontal Cortex

fMRI functional-Magnetic Resonance Imaging

psSME prestimulus Subsequent Memory Effect

$\overline{M}$ Mean

Chapter 1

General Introduction

1.1 Working memory models

1.1.1 What is working memory?

What did you eat last night? Everyone would agree that we need to tap into our memory storage in order to find the correct answer. While this question seems trivial, how we encode, maintain and retrieve information from memory has been object of interest for over a century. Two distinctive memory processes were engaged when answering the question above: a system that allowed us to maintain the question in our present awareness and a system from which the answer is retrieved. The concept of a two-systems memory was proposed back in the 19^{th} century by the seminal work of Wilhelm Wundt and Ernst Meumann and has received scientific attention ever since (Atkinson and Shiffrin, 1971).

Early influential models of memory (Atkinson and Shiffrin, 1971; Norman, 1968) identified a long-term store (LTS) in which long-lasting information is stored and a short-term store (STS), where information is stored temporarily and whose processes are under the immediate control of the individual. The whole memory system was described in terms of flow of information in and out the STS. The environmental input is processed by sensory registers and then transferred to the STS with the aid of selective attention. The information stored in STS was thought to quickly dissipate unless control processes that are under the control of the subject are activated (such as overt or covert rehearsal). While in STS, information could be copied in LTS to form long-lasting representations. Finally, to retrieve from the LTS, the subject has to use selection strategies to place some information in the STS. This information probes the activation of subsets of representations from the LTS. These subsets are then transferred to the STS where representations are scanned and examined to produce a response output. Hence, the STS functions as a buffer in which both the newly encoded and the retrieved information is temporarily maintained and examined by the subject through cognitive action. The number of information that can be temporarily stored in the STS was considered limited to seven to nine items.

The concept of the STS in the early models has laid out the basis for the investigation of what is now referred as working memory (WM). Some aspects such as the limited capacity, the action of attention, the online manipulation of information for maintenance and selection are still key features of the current conceptualization of WM. However, in the past decades the construct if WM has evolved into a variety complex models that have attempted to best describe cognitive and behavioural performance. WM is indeed believed to be central to language comprehension (Baddeley, 2003), learning (Wagner, 1999), reasoning (Süß et al., 2002) and numerical processing (Raghubar et al., 2010). Playing WM a key role in such fundamental cognitive processes, the understanding of its functioning has important real-life implications. In educational contexts, interest has grown in understanding the link between WM and learning disabilities (Brandenburg et al., 2015; Maehler and Schuchardt, 2016; Peng et al., 2016) and general academic achievement (Alloway, 2009). The ultimate aim is developing tools that may help specific populations during schooling and beyond (Redick et al., 2015; Roberts et al., 2016; Titz and Karbach, 2014) through WM training. In the clinical context, the study of WM has informed the understanding of several conditions such as anxiety and panic disorders (Moran, 2016; Silva et al., 2017), depression (Rose and Ebmeier, 2006), attentional deficits (Stroux et al., 2016), schizophrenia (Lett et al., 2014), and various forms of dementia (Beato et al., 2008; Iachini et al., 2009; Kirova et al., 2015). Given the extent of WM impairments in clinical conditions, research has been conducted to assess the temporal and spatial neural correlates of WM. Neurologically, WM has been found to be linked to prefrontal, temporal, parietal and premotor areas (D'esposito and Postle, 2015; Pessoa et al., 2002) and to be correlated with several oscillatory frequencies (Roux and Uhlhaas, 2014) and ERP components (Vogel et al., 2005).

1.1.2 Models of WM

Influential models of WM

Early models of memory conceptualized the STS as a unitary limited capacity system that fed information into the LTS. The STS also acted as a WM system, supported learning, retrieval of old information and complex cognition (Atkinson and Shiffrin, 1971). This early view was later challenged by the work of Alan Baddeley. Baddeley (Baddeley, 1992, 2003; Baddeley and Hitch, 1974) proposed a tripartite system of WM. The system was composed of the *central executive* that functions as an attentional control system, a storage for visuospatial information called the *visuospatial sketchpad* and a storage for verbal information called the *phonological loop*. Later, a fourth component was added to the model, the *episodic buffer*. The episodic buffer serves as a passive storage for multidimensional episodes and combines multisensory information (Baddeley, 2010). In the model, the four components interact allowing the information to be processed in parallel across the subsystems rather than reflecting a single flow of information (Baddeley, 2010).

The relevance that Baddeley's model has for the framework upon which this thesis has been developed lies in the key role of the central executive. The central executive coordinates information from the other subsystem which are referred to as slaves systems. The definition of the central executive was initially a broad and vague idea of control processes. Later, specific attentional processes were defined as agents of executive control. The first process to be identified was the ability of maintaining the focus of attention. Because the central executive is thought to be a limited capacity system, increasing attentional demands should impair performance. In a study in which a task put high demand on the central executive, several secondary tasks were administered in order to selectively disrupt the visuospatial and phonological subsystems (Robbins et al., 1996). Performance was indeed impaired when a secondary task that itself required high attentional processing was to be performed. The second attentive component identified in the central executive was divided attention. Studies on patients with deficits at the level of the central executive (Baddeley et al., 1991) performed significantly worse than controls when required to perform a dual task. However, their performance did not significantly differ to controls when increased level of difficulty was applied to a single task, supporting the idea that divided attention was a key component of the central executive (Baddeley et al., 2001). The third process is switching, namely the ability of switching attention from one object to another and between different tasks. However, Baddeley considered attention switching to be a process that did not only contribute to the functioning of the central executive but that may also depend on the phonological loop (Baddeley, 2002).

The model of Baddeley does not provide a complete framework of the functioning of WM. However, it has provided substantial advancements in its understanding. The major contribution of this model is the conceptualization of a multi-system model of WM and the role of attentional resources as modality-free control over the processing of information. In my opinion, a shortcoming of such model is the lack of definition of what constitutes the limited capacity of such system. Baddeley acknowledges that the slaves systems and the central executive have limited resources. Furthermore, he emphasizes how the episodic buffer constitutes limited storage where information is integrated from the slaves systems through the action of the central executive (Baddeley, 2001). However, the work of Baddeley does not further explain what are the mechanisms through which representations gain or gain not access to memory.

Models that have better addressed the issue of WM capacity are attentional models (Cowan, 2001; Engle, 2002). According to the view of Engle, WM capacity is defined as the domain-free limitation in the ability to control attention. Hence, WM capacity is conceptualized as isomorphic to executive attention. Central to the view of Engle is the idea that greater WM capacity does not reflect a bigger storage space, but a more efficient ability to use attention to avoid distraction and maintain information in a retrievable state (Engle, 2002). Dealing with proactive interference is indeed thought to be one of the main functions of WM (Engle, 2002; Kane and Engle, 2000). Proactive interference is when information in LTM interferes with the learning of new information. Engle (2002) reports the example of parking a car at the mall: after parking several times at the same mall we might have difficulty in recalling where we last parked our car because of the interference of previous memories. Kane and Engle (2000) linked WM capacity to the ability of dealing with proactive interference by observing that participants with high WM span were more vulnerable to proactive interference during a dual task than their low WM span peers. That suggested that high-WM span subjects relied more on attentional resources to reduce interference. Overall, Eagle's model provides a definition of WM capacity and its functioning in terms of the ability of controlling executive attention and of inhibiting the interference of distractors, while rejecting the notion of WM capacity as storage space.

A substantially different view of the concept of WM capacity is proposed by Cowan (Cowan, 2001). Central to his theoretical framework are the ideas that the focus of attention is capacity-limited, that in adults the limit of such focus averages to four chunks, and that any information deliberately recalled is restricted to such limit of attention. *Chunks* are defined as discrete grouping of information that have strong associations to one another and weak associations with other groups of information. Chunks can be activated from LTM on the basis of the current environmental context for which these chunks are relevant. Activated chunks then enter the limited focus of attention, making them available to conscious awareness. Other authors have investigated the idea that only a few items can be temporarily and simultaneous be maintained, however there is no resolved consensus on the exact number (Cowan, 2001; Miller, 1975, 1956).

Cowan's model differs from Engle's. According to Cowan, capacity is determined by a limited and well defined number of representations that can be retained in memory. Nevertheless, they agree over the centrality of attention in determining WM capacity. Indeed, it is important to stress that according to Cowan's view, capacity is not intended as passive storage of information, but rather as available space within the focus of attention.

In summary, the models presented above all agree with the concept of WM being limited in capacity and with the importance of attention to make information readily available to consciousness. There is however major difference between Baddeley's model and the attentional models. According to Baddeley, the storage systems are conceptualized as distinct from attentional control. According to attentional models, WM capacity is thought to be essentially of attentive nature. Nevertheless, all three models have been essential for understanding WM. In particular, the concepts of limited capacity, the idea of discrete representations and the importance of attentional resources are all fundamental for understanding the debate between *slot models* and *resource models* of WM.

Slot models and resource models of WM

The concept of WM as a system that holds a limited number of items has influenced the development of *slot models* of WM. According to this approach, visual stimuli are stored in WM in a small fixed number of memory slots. Those items that are encoded in memory and that gain access to one of the slots are remembered in high-resolution with all the features bound together. On the other hand, items that do not gain access to any of the slots are completely forgotten (Awh et al., 2007; Luck and Vogel, 1997; Rouder et al., 2008; Vogel et al., 2001; Zhang and Luck, 2008). The mean through which items gain access to the slots is selective attention (Donkin et al., 2015).

Data in support of these models mainly come from change-detection tasks. These tasks consist of arrays of items (e.g. coloured squares). Sample arrays are followed by a brief retention interval and then by a test array. The test array could either be identical to the sample array or be different in one feature or one single item. The task of the participant is to judge whether the test array is different from the sample array (Fig. 1.1). Using this paradigm in their seminal paper, Luck and Vogel (1997) showed that performance to a change detection task was perfect for set sizes up to 3 and systematically declined as set size increased. These results were explained as representing failed encoding for items that did not gain access to memory slots. Support to this hypothesis also came from electroencephalography (Vogel and Machizawa, 2004) and fMRI studies (Todd and Marois, 2004; Xu and Chun, 2006) that showed that neural activity reaches a plateau at high memory loads. However, the methodology of these studies has been put into question (Ma et al., 2014).

Another important feature of slot models is that items that are encoded in WM are precisely recalled with all their features bound together. In Luck and Vogel (1997), items were oriented bars in which either orientation or colour could change. Participants' performance at set size four was identical whether only one or both features changed in the test array. These results supported the hypothesis that items are encoded in WM as perceptually integrated objects.

Critiques to slot models identified as problematic the experimental paradigm used to assess WM capacity (Ma et al., 2014). Indeed, change detection tasks use discrete stimulus sets. Hence, memory recall for objects can only be evaluated in a binary fashion (recalled or not recalled).

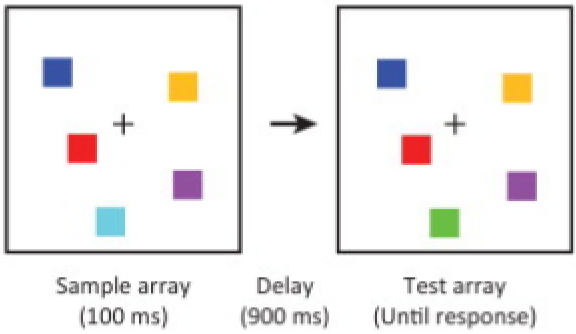

Figure 1.1 Example of the change-detection task using coloured squares (taken from Luck and Vogel, 2013). The memory array (left panel) is presented followed by a retention interval. Then, a test array is presented where one item might have changed in one of its features (in this example, colour). The participant has to judge whether the test array is identical or different from the memory array.

Data from studies that investigated precision of recall using delayed-estimation tasks have raised doubts on the validity of slot models. In delayed-estimation tasks, sample items vary on continuous variables such, as the orientation of a bar in a 360°space or colours from a colour wheel. After a retention interval, participants are asked to report the features of a probed sample item as accurately as possible. Performance is measured by precision of recall (e.g., Bays et al., 2009; Gorgoraptis et al., 2011), meaning the deviation of the feature values reported by the subject from the feature values of the probed item. These studies observed that precision of recall continuously decreases with increasing number of items in a sample array (Bays et al., 2009; Bays and Husain, 2008). Moreover, when an item is cued, its precision of recall increases at the cost of the other memory items (Bays et al., 2011a). These findings could not be explained by slot models according to which items that gain access to a slot are perfectly remembered in all their features and items that do not gain access are simply not encoded.

An explanation of the above findings was given by *resource-models* of visual WM. According to these models, WM is a limited resource system whose resources are flexibly allocated to all of the items in an array (Bays et al., 2009, 2011a; Bays and Husain, 2008;

Bays et al., 2011b; Gorgoraptis et al., 2011; Ma et al., 2014; Pertzov et al., 2013; Wilken and Ma, 2004). Hence, the more the resources are distributed across items, the poorer is the quality of the representations. But what exactly determines the decrease in quality representations? Central to the theorization of resource models is the concept of noise. The representation of each item in memory carries a certain level of stochastic noise. Increasing the number of items to be retained increases the overall noise in WM as a function of the reduction of available resources per item (Ma et al., 2014). Noise can affect WM at encoding (Bays et al., 2011a; Mazyar et al., 2012), maintenance (Pertzov et al., 2013) and recall stages of processing (Ma et al., 2014).

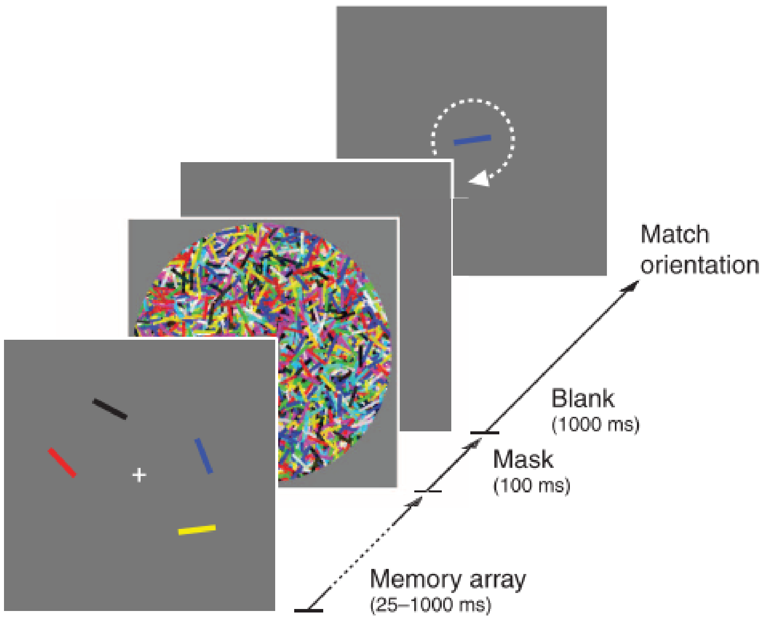

Figure 1.2 Example of a trial in a delayed-estimation task taken from Bays et al. (2011a). The memory array contains items whose features vary on a continuous scale (for instance, orientation). After a retention period, one of the memory items is probed. The participant has to adjust the features of the test item to match those of the probed item. In this example, the participant has to reproduce the same orientation of the blue bar in the test array.

Another central aspect of resource models is that resources are not only distributed across items, but also flexibly allocated (Ma et al., 2014). For example, Gorgoraptis et al. (2011) showed that, in a delayed-estimation task in which sample stimuli were presented sequentially, precision of recall was better for items that had been cued compared to other items in the sequence. Furthermore, in Bays et al. (2011a) cued items had enhanced quality of recall even if they were cued retrospectively. These results are taken as supportive of the idea that WM is constituted of attentional resources that can be voluntarily allocated to task-relevant stimuli.

As introduced above, precision of recall is measured by the deviation of the reported value from the exact value of the sample item. Behavioural modelling has shown that deviations follow a Gaussian-like distribution centred at the sample item value. Deviations from the target value are generally referred to as errors. Specifically, for features whose values are drawn from a 360°space, errors are distributed over a Von Mises distribution, which is a wrapped Gaussian distribution with mean zero. Zero refers to no deviation from the correct value (e.g., Bays et al., 2009). However, it became apparent that memory quality was not the only contributor to recall errors. Indeed, a series of studies showed that the features of non-target stimuli in the memory array also influence precision of memory recall (Bays et al., 2009, 2011a,b; Gorgoraptis et al., 2011). In other words, reporting errors are also distributed around the feature of non-target items.

Trying to make sense of reporting errors has brought to the theorization of a model that it is somehow a compromise between slot and resource models: the *discrete representation model* (Zhang and Luck, 2008). According to this model, memory resolution depends on a small set of discrete, fixed-resolution representations and these slots are described as a type of resource. Slots are shared across different items, but if an item is more relevant or the number is small, more slots are devoted to the same item. However, similarly to the slot model proposed by Luck and Vogel (1997), slots maintain their discrete fashion and only a limited number of items can be encoded. Hence, some items will not gain access to WM. The discrete representation model explains the data with a Gaussian+uniform distribution. The uniform distribution accounts for errors generated by random guessing when no representation of the item has been encoded in memory.

Overall, these models attempt to provide a detailed description of how WM processes visuospatial information and constitute a major advancement in the understanding of WM. What class of models best explains visuospatial WM functioning, is still a heated debate.

1.1.3 The relevance of WM models for the present thesis

In the present thesis, theoretical models of WM informed experimental choices taken in order to assess the effect of anxiety on WM. In particular, in the planning stages of this research, the non-dichotomous nature of paradigms assessing resource models appeared to potentially offer a better tool for the assessment of the effect of physiological arousal on memory. Anxiety does not elicit a dichotomous response. In fact, it can rather be described as a continuous physiological activation that interacts with the subjective perception of threat (Sussman et al., 2016). Hence, the paradigms developed to assess resource models of WM (Bays et al., 2011a,b) were adopted the the present experimental work in order to assess the extent to which anxious arousal affects the noise of representations on WM.

1.2 WM and maths processing

WM has been found to aid numerous high level cognitive processes and its correlation with maths processing has been widely reported (Adams and Hitch, 1997; DeStefano and LeFevre, 2004; Peng et al., 2016; Raghubar et al., 2010). Performing arithmetic engages complex skills and it requires to hold information in memory while manipulating it. Hence, not surprisingly the link between WM and maths processing has received much attention in the past decade. Furthermore, being able to perform maths has great impact in our daily lives. First, it is required in a great number of everyday situations (e.g. counting money). Second, maths performance plays a big role in overall academic achievement. The extent of the importance of maths abilities has suggested the practical relevance of investigating the relationship between WM and maths cognition and developing tools for WM trainings, although their effectiveness is still debated (Holmes and Gathercole, 2014; Melby-Lervåg and Hulme, 2013).

1.2.1 Contribution of subsystems of WM to maths processing

In order to solve arithmetic problems, the necessary information must be encoded and maintained in memory (DeStefano and LeFevre, 2004). Experimental evidence has suggested that both the visuospatial and phonological components of WM are involved in these processes and their different contribution seems to be modulated by presentation format (Trbovich and LeFevre, 2003), presentation duration (Noël et al., 2001) and presentation modality (Logie et al., 1994). However, the literature on the specific contribution to the individual WM subsystems is not conclusive (DeStefano and LeFevre, 2004). The reason might be that mental arithmetic might engage different processes according to the type of arithmetic operation, the type of stimuli presentation and the strategies used for problem solving (DeStefano and LeFevre, 2004).

The phonological loop seems to be involved during counting in additions, subtractions and multiplications (Hecht, 2002; Lee and Kang, 2002; Lemaire, 1996; Seyler et al., 2003) and it has been linked to the ability of maintaining intermediate results during calculation (Logie et al., 1994; Seitz and Schumann-Hengsteler, 2002). However, evidence for the involved of the phonological loop is inconsistent. For example, Lemaire (1996) showed that articulatory suppression impaired performance at a verification task, while De Rammelaere et al. (2001) did not. Furthermore, Friso-van den Bos et al. (2013) found that verbal updating was strongly correlated with maths abilities. On the other hand, Passolunghi et al. (2007) suggested that phonological ability is not involved in mathematics learning ability. It is possible that such contrasting results depend on the fact that different strategies used for arithmetic problem solving tap into the verbal subsystem of working memory to a different extent (Raghubar et al., 2010). Moreover, some of the studies might have failed to isolate the involvement of the phonological loop from that of the central executive (DeStefano and LeFevre, 2004).

The visuospatial subsystem of WM has also received attention in the study of maths processing. In dual-task procedures, visuospatial interference disrupted performance during subtraction (Lee and Kang, 2002) but not multiplication (Lee and Kang, 2002; Seitz and Schumann-Hengsteler, 2000). In a longitudinal study with preschoolers and schooling children, Bull et al. (2008) found that visuospatial WM was a predictor of maths ability. Evidence for the possible importance of visuospatial WM abilities for maths processing also comes from specific populations. For example, children with specific maths learning disabilities seem to have a primary deficit of visuospatial WM (Szűcs, 2016; Szűcs et al., 2013). They have been found to fail at spatial WM tasks if compared to controls (Passolunghi and Mammarella, 2012). Furthermore, children with nonverbal learning disabilities had poorer performance at calculation compared to controls (Mammarella et al., 2010).

The evidence for the role of the central executive for maths processing comes from several studies. In a dual task experiment in which central executive load was increased while performing mental additions, performance was impaired regardless of the modality (visual or auditory) in which the addends were presented. Thus, providing evidence of a modality-free involvement of the central executive during mental arithmetic (Logie et al., 1994). It has been proposed that the central executive supports the maintenance of interim results during mental calculation. Indeed, studies on mental arithmetic that required to decompose the solving of the operation is steps (for example with operations with *carry*) showed a decrement in performance with increased central executive load (Fürst and Hitch, 2000; Seitz and Schumann-Hengsteler, 2000, 2002). Furthermore, executive functions such as inhibition and switching play a critical role in maths proficiency and are predictors of maths ability (Bull and Scerif, 2001; Cragg and Gilmore, 2014).

1.3 Neural evidence for different systems in WM

A multi-system conceptualization of WM explains dissociations in behavioural tasks. Hence, neuroimaging studies have investigated whether such dissociation is also reflected in distinct neural correlates.

Areas that have robustly been found to be correlated with WM functioning are the lateral premotor cortex, the dorsal cingulate and medial premotor cortex, the dorsolateral and ventrolateral prefrontal cortex, the frontal poles, and medial and lateral posterior parietal cortex. Interestingly, these areas were found to be activated for both verbal and visuospatial stimuli and it has been suggested that they might be central for control and organization of information in WM (Bor et al., 2004; Curtis and D'Esposito, 2003; Johnson et al., 2005; Owen et al., 2005). Furthermore, the activity of the prefrontal cortex has been found to correlate with fluid intelligence (Duncan and Owen, 2000). Hence, these areas might reflect the neural correlates of the central executive (fig 1.3).

Neural data seem to provide some evidence of the dissociation between visuospatial and verbal WM (Nee et al., 2012; Owen et al., 2005). It has been reported that caudal superior frontal sulcus is sensitive to spatial information, while the midlateral prefrontal cortex showed sensitivity to non-spatial content (Nee et al., 2012). Furthermore, in their metanalysis focusing on the n-back task, Owen et al. (2005) suggested that the left prefrontal cortex showed verbal dominance, while the premotor cortex showed spatial dominance. Regarding the dolsolateral prefrontal cortex, in Bor et al. (2004) it was found to be activated independently of stimulus modality, but Fried et al. (2014) demonstrated a dissociation of verbal and spatial WM. Specifically, stimulating the right dorsolateral prefrontal cortex improved verbal WM performance but did not have any effect on visuospatial WM performance.

What are the neural correlates of WM and its sub-systems is an intriguing question in its own right. While it is out of the scope of the present thesis to investigate the localization of the WM sub-systems within the brain, neural evidence of WM dissociation has informed studies that seek to underpin the mechanisms through which anxiety affects performance to tasks requiring WM. In particular, it has informed the understanding of how the subsystems WM may compete for resources with anxiety-induced processes. This is particularly important for the understanding of those types of anxieties, such as maths anxiety (MA), for which the relationship between anxiety and task performance is thought to be mediated by WM. These points are further elaborated in the following sections looking at the WM-anxiety interactions and its key role in determining MA.

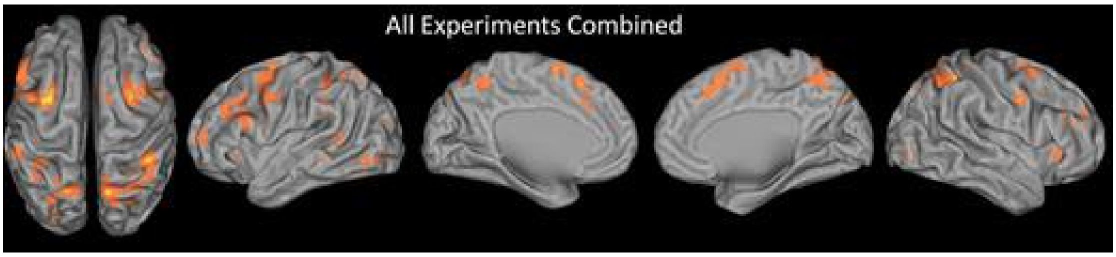

Figure 1.3 Neural correlates of executive control as found in Nee et al. (2012) metanalysis.

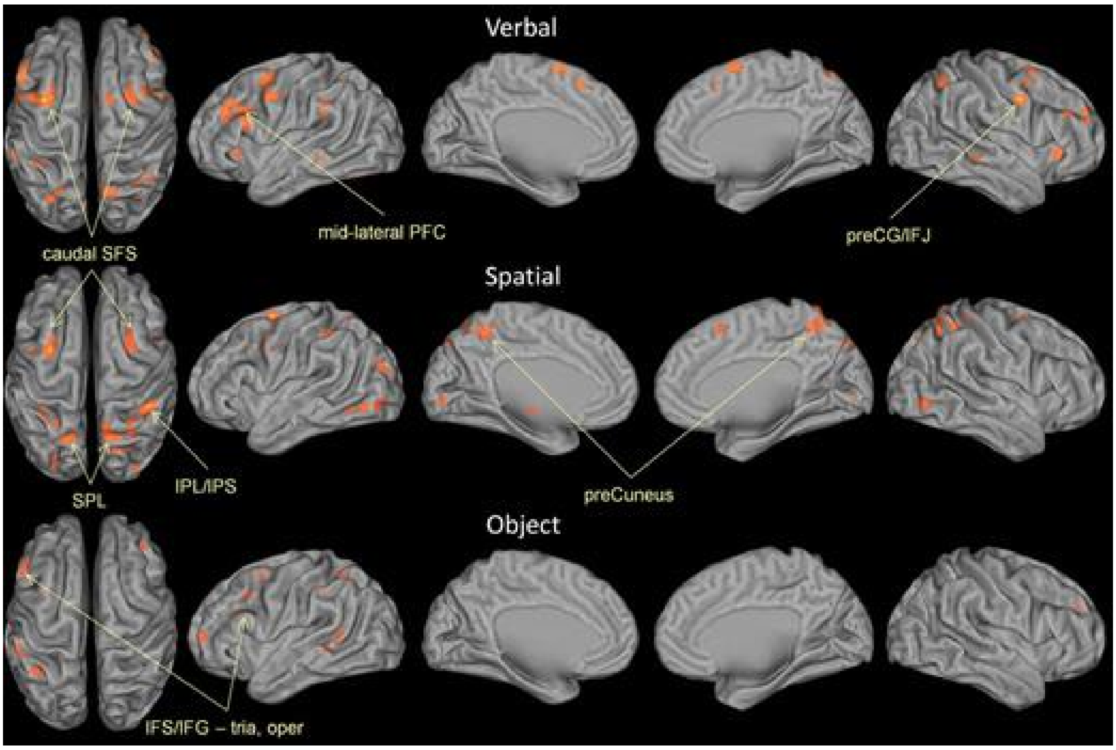

Figure 1.4 Modality-specific neural correlates of WM as found in Nee et al. (2012) metanalysis.

1.3.1 The relevance of the relationship between WM and maths processing for the present thesis

In summary, the importance of subsystems of WM in maths processing has been widely investigated. Furthermore, performance on maths tasks can be significantly affected by anxiety, ultimately resulting in a great impact on life choices (Ashcraft, 2002; Ashcraft and Kirk, 2001). The understanding of the mechanisms through which anxiety affects WM may therefore offer an insight into how everyday tasks that rely on WM processes, such as maths performance, are affected by it. In particular, the understanding of how the different systems of WM contribute to maths processing has informed the choice of investigating the effect of anxiety on visuospatial WM in chapter 2.

1.4 Effects of anxiety on WM

Anxiety is an emotional state that occurs when an individual faces threat to self-preservation (Eysenck and Calvo, 1992). It is a multidimensional construct than encompasses personality, emotion, cognition and physiology (Eysenck et al., 2007, 2005; Eysenck and Calvo, 1992). Clinically, a study reported that during a lifetime up to 33.7% of the population are affected by an anxiety disorder (Bandelow and Michaelis, 2015). However, anxiety is not only a clinical condition, but also an adaptive response to threat. In the presence of danger, it facilitates sensory processing and it initiates cognitive and physiological changes that prepare the individual to activate defence mechanisms aiding self-preservation (Baas et al., 2006; Grillon, 2008). However, anxiety has been found to impair performance in several cognitive tasks (Eysenck and Calvo, 1992).

In the following sections, I am going to introduce how anxiety influences cognitive processing with a focus on WM. Then, I will introduce some physiological measures of anxiety that have been relevant for the development of the present research project.

1.4.1 Anxiety and cognition

Attention bias

Anticipation of future threats is a central aspect of anxiety. Anxiety is elicited by unpredictable harm and by distal, potential or symbolic threats. For example, in a study in which the administration of threatening stimuli was signalled or not-signalled, the unpredictability of the not-signalled condition induced higher anxious responses in participants (Grillon et al., 2004). At the subjective level, anticipation of threat results in tension, worry and feeling of insecurity (Grillon, 2008). At the cognitive level, it is characterized by attentional changes such as enhanced and sustained vigilance (Blanchard et al., 1993), and attention bias (Cisler and Koster, 2010). Attention bias has received wide interest in literature and it is at the centre of the most influential models explaining the effects of anxiety on cognition (Cisler and Koster, 2010). Experimental research has shown that anxiety facilitates attention towards threatening stimuli and it has been observed in studies using several different paradigms involving both verbal and spatial judgements (Cisler et al., 2009). As examples, in a modified

Stroop task (Stroop, 1935), threatening and neutral words are displayed in different colours. Participants are required to report the colour ignoring the the semantic meaning of the words. Delayed responses for threatening words have been reported in several clinical populations (Bar-Haim et al., 2007). In the dot-probe task (MacLeod et al., 1986), two words (threatening or neutral) are displayed on a screen. After words offset, a probe appears at the location of one of the words and the participant has to indicate what word was replaced by the probe. It has been shown that anxious participants respond faster when the probe replaces the threatening stimulus, possibly as a result of the attentional preference for threat (Bar-Haim et al., 2007; Bradley et al., 1999). Another effect that anxiety has on attentional processes is an increased difficulty in disengaging attention from a threat stimulus (Cisler et al., 2009; Fox et al., 2002). Furthermore, some studies have also observed attentional avoidance in high anxious participants (Koster et al., 2006; Mogg et al., 2004).

In summary, the anxiety-induced attentional bias has been widely reported in literature. In the framework of the present thesis, the influence that anxiety has on attentional resources is considered the chain ring that allows us to grasp how anxiety affects WM.

Models

The *Attentional Control Theory* (ACT) from Eysenck and Calvo constitutes the most influential theory explaining how anxiety impacts performance at cognitive tasks. It places attention at the centre of the relationship between anxiety and performance. The theory generates from the assumption that anxiety increases attention to threat-related stimuli at the cost of task-related stimuli (Eysenck et al., 2007). Such assumption links to the idea that there are two attentional systems (Corbetta and Shulman, 2002). One is the goal-directed system which is guided by expectations and it exerts top-down control over attention. Neural correlates of this system have been identified in the prefrontal cortex. The second is the stimulus-driven system which is influenced by the salience of the stimulus and it regulates attention via bottom-up processes. The neural correlates of this system have been localized at temporoparietal and ventral frontal areas. While these systems usually interact with each other in an adaptive manner (Pashler et al., 2001), according to the ACT anxiety disrupts such balance resulting in a increased action of the stimulus-driven system at cost of the goal-directed system (Eysenck et al., 2007).

Attentional imbalance is thought to impact performance through its effects on the central executive as conceptualised by (Baddeley, 1992). Specifically, the ACT explains the attentional effects of anxiety over three executive functions as identified by Miyake et al. (2000): inhibition, shifting and updating. Inhibition consists in the ability of using attentional control to resist task-irrelevant stimuli. Shifting is the ability to adapt attentional control on the basis of task demands. Updating is the monitoring of working memory representations. According to the ACT, anxiety impairs the inhibition function (Eysenck et al., 2007). Hence, anxious individuals will be less efficient in inhibiting task-irrelevant stimulation. Task-irrelevant stimulation is intended not only as external threats but also internal thought of worry and ruminations.

As a result of impaired inhibition, anxious individuals will have less available resources to devote to the task. Evidence for this account comes from studies that observed reduced WM storage and processing in anxious participants (Darke, 1988; MacLeod and Donnellan, 1993; Owens et al., 2012). Such effect is greater in tasks that require high demands on the central executive (Ashcraft and Kirk, 2001). However, it is important to mention that anxiety does not always translate into poorer performance thanks to the engagement of compensatory processes (Eysenck et al., 2007). Furthermore, participants that have high WM might benefit from high anxiety as additional motivation to perform well (Owens et al., 2014).

Neuroscientific studies have also brought evidence in support of the relationship between anxiety and central executive functions. Anxious individuals show reduced recruitment of prefrontal areas suggesting that anxiety hinders attentional control (Bishop et al., 2004; Bishop, 2007, 2009; Fales et al., 2008). Furthermore, ERP studies have reported higher amplitudes of the P1, P2 and P3 components in anxious individuals when exposed to threat (Bar-Haim et al., 2005; Carretié et al., 2003; Eldar and Bar-Haim, 2010; Li et al., 2006, 2005). The P1 has been found to be a correlate of visuospatial orienting of attention (Luck et al., 1990), the P2 of attention disengagement (Bar-Haim et al., 2005), and the P3 of strategic orientation of attention (Polich, 2007).

The alternative *two-components* model has been proposed after observing that the impairment of performance is reduced when subjects engage in a difficult task that occupies executive resources (Vytal et al., 2012). The model suggests that when WM tasks are easy, there are free resources for anxious apprehension to engage and therefore the effect of anxiety is greater. The two components model also theorizes a differential effect of anxiety on verbal and visuospatial WM. According to the model, engaging in a high load verbal WM task reduces the impact of anxiety by engaging top-down emotional control mechanisms. On the other hand, the effect of anxiety on high-load visuospatial WM is not attenuated. That is because anxiety and visuospatial WM compete for resources of defensive mechanisms, such as perceptual sensitivity and autonomic arousal which are independent of WM load. Vytal et al. (2013) found that induced anxiety disrupted more low and medium-load verbal WM compared to high-load and that visuospatial WM was disrupted regardless of task difficulty.

Finally, Shackman et al. (2006) proposed the *hemispheric asymmetry hypothesis* according to which anxiety uniquely disrupts spatial WM performance accuracy. The reason would be that task-irrelevant anxious arousal and attentional processes compete with spatial WM processes for resources in the right prefrontal cortex and other more posterior regions (Lavric et al., 2003; Shackman et al., 2006).

While the three models may predict different experimental outcomes, they are not mutually exclusive. Indeed, all models are centred around the crucial interplay between anxiety and attentional control. The effect of anxiety over attentional mechanisms is solidly corroborated by experimental research.

1.4.2 Can poor performance induce anxiety and reduce WM capacity?

The models explaining how WM mediates the relationship between anxiety and performance assume a specific causal direction. Namely, the models explain how anxiety has a detrimental effect on performance. However, may the relationship be explained by the opposite causal direction? Can performance induce anxiety that reduces WM capacity? Some studies suggest that individuals with poor performance at tasks involving WM report higher levels of anxiety (Passolunghi, 2011; Rubinsten and Tannock, 2010). This may suggest that poor performance may induce anxiety. However, it is important to note that these studies mainly focus on learning settings while, to the best of my knowledge, the literature is lacking a more generalizable investigation of the role that poor performance plays in inducing anxiety. Moreover, deficits in WM are thought to characterize learning disabilities (Fias et al., 2013; Mammarella et al., 2015, 2010). In such cases, poor performance might induce anxiety. However, that provides an explanation for clinical populations but cannot answer the question on whether poor performance reduces WM capacity through means of anxious arousal in non-clinical subjects. Such gap in the literature may be either justified by failure to provide evidence for such causal direction of the relationship. On the other hand, researchers might have simply overlooked to possibility of such directionality. In summary, the question remains open and unanswered. Understanding whether is certain cases poor performance reduces WM capacity through anxiety would be very important in directing and targeting tailored interventions.

1.4.3 Anxiety and physiology

Anxiety induces physiological arousal that will prepare the body for a rapid behavioural response to danger (Marks and Nesse, 1994). Symptoms of physiological arousal caused by anxious states are thought to reflect activity of the autonomic nervous system (ANS) (Thayer et al., 1996). The ANS can be divided into the sympathetic and parasympathetic branches that, from the brain stem and through the spinal cord, innervate the cardiovascular and visceral systems. The coordinated activity of the two branches prepares the body to respond to threat in emergencies or stressful situations (Jänig and McLachlan, 1992). Anxiety is characterized by sympathetic activation and parasympathetic deactivation which cause a series of physiological reactions, including increase in heart rate (HR), increase in blood pressure, decrease in fingers temperature, increase in respiratory rate and oxygen consumption, and increase in the variation of the electrical properties of the skin in response to sweat secretion (skin conductance) (Benedek and Kaernbach, 2010; Kreibig, 2010). Although not exhaustive, in the following section I will introduce some of the physiological measures used to assess anxiety.

Startle

The *fear/anxiety-potentiated startle reflex*, or simply *startle*, is an ubiquitous, cross-species response to abrupt and intense stimulation. It manifests as a rapid sequential muscle contraction that has evolved to facilitate the flight reaction and to protect the body from a sudden attack. While it has the characteristic of being stereotyped, its amplitude measured through electromyography (EMG) shows high variability that reflects variation in the internal state of the organism (Grillon, 2008; Grillon and Baas, 2003; Hamm and Vaitl, 1996). The startle reflex has gained popularity as a measure to infer psychological states for several reasons. It is an automatic response that is not influenced by intentional control; it is resistant to response bias that usually affects verbal reports and voluntary motor responses such as reaction times; it can be elicited at any time to probe ongoing affective processes; it has high sensitivity to habituation, sensitization, sensorimotor gating, and affective modulation; it is easy to elicit and quantify (Grillon and Baas, 2003; Hamm and Vaitl, 1996). In psychophysiological research, the startle is usually elicited with abrupt bursts of white noise and it is measured through the EMG of the orbicularis oculi muscle (Blumenthal et al., 2005). At the neurological level, the startle has been found to be regulated by the activity of the amygdala and the bed nucleus of the stria terminalis. The latter is responsible for responses to uncertain and durable threats as in the case of general anxiety, context conditioning and chronic stress (Gewirtz et al., 1998; Grillon and Davis, 1997; Richardson and Elsayed, 1998).

A successful protocol that has been developed to study anxiety by measuring the startle reflex is the *NPU-threat test* (Schmitz and Grillon, 2012), which has been readapted in the research presented in this thesis. The test was originally developed to assess phasic and sustained stress responses in humans. The protocol, as described by Schmitz and Grillon (2012), is composed by three conditions. N, a safe condition in which no aversive stimulus is delivered; P, a condition in which predictable electric shocks are delivered; U, a condition in which unpredictable electric shocks are delivered. In the P condition, a visual cue signals the administration on the shock, while in the U condition the visual cue does not predict shock administration. The startle reflex is induced by the presentation of bursts of white noise.

According to Grillon and Baas (2003), the physiological arousal induced by the unpredictable condition reflects anxious states, as the uncertainty of threat creates a sense of sustained tension. Research on clinical populations has proved the NPU-threat test to be an effective method to study anxiety disorders. For example, it has been shown how individuals with panic disorder or post-traumatic stress disorder (PTSD) are selectively more sensitive to the startle elicited in the unpredictable condition than in the predictable condition (Grillon et al., 2008).

Cortisol and skin conductance

The activation of the sympathetic nervous system during a stressful situation activates the hypothalamus-pituitary-adrenal (HPA) axis which results in an increase of cortisol concentration in the blood and in the saliva (Gaab et al., 2005; Sapolsky et al., 2000). Levels of cortisol within the system physiologically change during the day due to circadian rhythms. Disregulation of blood and salivary cortisol levels has been found in anxiety disorders (Hek et al., 2013; Mantella et al., 2008; Vreeburg et al., 2010). Increases in cortisol responses to stressful situations are considered a marker of acute stress (Armario et al., 1996; Berger et al., 2016). Furthermore, cortisol responses to stress have been found to mediate WM and executive functions. However, the literature is inconsistent in identifying the direction of the relationship between cortisol levels and cognitive performance (Al'Absi et al., 2002; Duncko et al., 2009; Robinson et al., 2008; Shields et al., 2016; Vedhara et al., 2000).

The skin conductance response refers to enhanced electricity conductivity of the skin as response to external events. The phenomenon occurs when increased nerve activity increases the number of sweat glands opening. Because the activity of the sudorimotor nerve is thought to reflect sympathetic arousal, fluctuations of skin conductance may reflect anxious responding (Bach et al., 2010). The relationship between anxiety and skin conductance is still not clear. While some studies reported enhanced skin conductance responses in anxiety disorders (Hinrichs et al., 2017), others have failed to detect such relationship (Glover et al., 2011; Marin et al., 2017; Rosebrock et al., 2016).

HR variability

The human heart is controlled by electrical discharges that stimulate contractions and that can be measured with the electrocardiogram (ECG). The cyclic depolarization and repolarization of the heart ventricula generates the shape of the PQRST waves. The largest portion of the signal is the QRS complex (Fig. 1.5, left panel) which is caused by ventricular depolarization (systole). The time between consecutive R-R peaks (also called *inter-beat-intervals*, IBIs) is highly irregular during steady-state conditions (Fig. 1.5, right panel) and it is referred to as heart rate variability (HRV). HRV is regulated by the action of the sympathetic and parasympathetic branches of the autonomic nervous system. Hence, analysing HRV can give information on autonomic balance (Peltola, 2012; Shaffer et al., 2014).

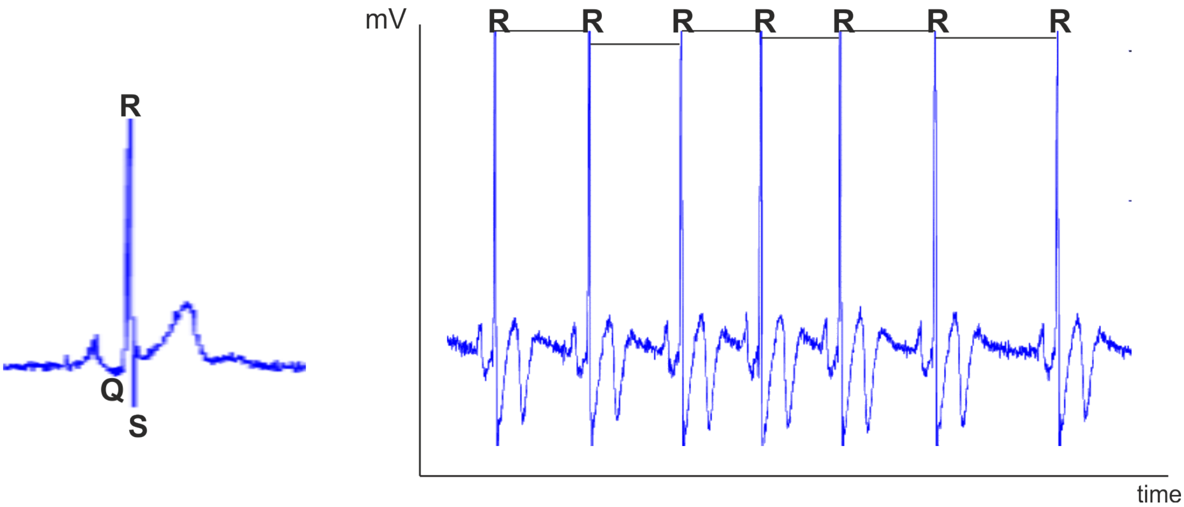

Figure 1.5 Left panel: the QRS complex caused by ventricular depolarization. Right panel: sinus rhythm of the heart. The duration of R-R intervals vary greatly and is a measure of HRV.

Short-term HRV [1] is influenced by dynamic autonomic balance and regulatory mechanisms such as the baroreceptor reflex, rhythmic changes in vascular tone, and the respiration-driven speeding and slowing of the heart via the vagus nerve (Shaffer and Ginsberg, 2017). Regarding autonomic balance, the parasympathetic system exerts effects over the heart faster (less than 1 second) than the sympathetic system (more than 5 seconds). The concurrent contradictory action of the two systems regulates HRV. Regarding regulatory mechanisms, their action on HRV is approximately in the range of 4 to 5 seconds (Shaffer and Ginsberg, 2017).

Optimal levels of HRV reflect physiological adaptability and self-regulatory capacity (Shaffer and Ginsberg, 2017). Higher levels of vagally-mediated HRV have been linked to the engagement of executive functions by the prefrontal cortex (McCraty and Shaffer, 2015). For example, Hansen et al. (2003) showed that higher resting-state HRV is associated with

[1]Long-term HRV, such as 24 hours recordings, will not be discussed here as it goes beyond the scope of this thesis

better performance at cognitive tasks engaging executive functions. Moreover, HRV during task performance is decreased compared to resting-states and it is lower if the tasks involve high cognitive load (Hansen et al., 2003; Hjortskov et al., 2004; Mukherjee et al., 2011; Taelman et al., 2011). HRV is also thought to reflect regulation of emotional responding (Appelhans and Luecken, 2006). For instance, individuals with reported scores of adaptive coping strategies to stress have been found to have higher resting-state HRV (Fabes and Eisenberg, 1997; O'Connor et al., 2002). Furthermore, patients diagnosed with anxiety disorders show chronic HRV reduction and PTSD patients show reduced HRV during the recalling of traumatic episodes (Chalmers et al., 2014; Martens et al., 2008).

Measures of HRV can be divided into two main groups: *time-domain* and *frequency-domain* measures. Because of the large number of available indices, here I will review those relevant for understanding the methodology adopted in the present reasearch project.

Time-domain measures Time-domain indices quantify HRV over periods that can range from just over 1 minute up to 24 hours. The mean and the standard deviation of the IBIs of normal sinus beats (SDNN) are calculated from recordings in which abnormally premature beats (ectopic beats) have been removed; hence the term "normal" is adopted to refer to R-R peaks. They are influenced by both branches of the autonomic nervous system and are a popular measure for short recording times of 5 mins (Malik et al., 1996). In short-term recordings, the primary influence is exerted by parasympathetically-mediated respiratory sinus arrhythmia (Shaffer and Ginsberg, 2017).

The root mean square of successive differences between normal heartbeats (RMSSD) is also a popular measure for short-term recordings (the standard is 5 min of duration). The RMSSD is calculated as following:

$$RMSSD = \sqrt{\frac{1}{N-1}\left(\sum_{i=1}^{N-1}\Big((R-R)_{i+1}-(R-R)_i\Big)^2\right)} \tag{1.1}$$

where N is the number of IBIs and R are normal R peaks.[2]

The RMSSD is the primary time-domain measure to estimate vagally mediated changes (Shaffer et al., 2014). The RMSSD is relatively unaffected by respiration compared to other measures (Hill et al., 2009) and it is more influenced by the parasympathetic nervous system than the SDNN (Shaffer and Ginsberg, 2017).

[2] $R-R$ refers to normalized R-R intervals in which ectopic beats have been removed.

Time-frequency measures The Fast-Fourier Transformation (FFT) is used to decompose the HR signal into frequency bands. The low-frequency (LF) band has 0.04–0.15 Hz boundaries and it requires a minimum of 2 minutes of recording. The parasympathetic and the sympathetic branches of the nervous system and blood pressure baroceptors contribute to LF power. However, the parasympathetic nervous system is believed to have more weight in determining LF power compared to the sympathetic nervous system (Shaffer and Ginsberg, 2017).

The high-frequency (HF) band has 0.15–0.40 Hz boundaries and it requires a minimum of 1 minute of recording. The HF band reflects parasympathetic activity and it is highly correlated with the respiratory cycle. HF power is also correlated with the RMSSD (Shaffer and Ginsberg, 2017).

The LF to HF ratio (LF/HF ratio) is based on the assumption that LF are mostly generated by sympathetic activity and that HF are mostly generated by parasympathetic activity. Hence, a high LF/HF ratio is thought to indicate a stress response with high sympathetic activity and parasympathetic withdrawal. However, some authors have argued that the relationship between the sympathetic and parasympatetic systems is not linear and that LF is not a pure measure of sympathetic activity (Billman, 2013). Furthermore, the influence of sympathetic activity over LF might be influenced by testing conditions (Shaffer et al., 2014).

1.4.4 The relevance of understanding anxious arousal for the present thesis

In summary, studies have demonstrated that anxiety can be effectively measured on-line by means of physiological indexes. Moreover, as suggested by Eysenck and Calvo (1992), physiological arousal may also contribute to ineffective attentional resource allocation, resulting in impaired WM performance. Hence, in the present work, some of the physiological measures of anxiety have been adopted in order to investigate the relationship between anxiety, WM and maths processing. In particular, HRV measures and the startle reflex have been chosen to answer the research questions in chapters 3 and 4.

1.5 MA and physiological measures

Maths anxiety (MA) refers to a debilitating negative emotional reaction to mathematical tasks and it may occur in both children and adults (Ashcraft, 2002; Ma, 1999). MA is typically measured by self-report questionnaires in which individuals rate their agreement or

disagreement on a series of sentences referring to everyday situations involving maths. It has been reported that MA has great negative impact on both children's and adults' mathematical education: it contributed to the development of negative attitudes towards tasks involving maths (Devine et al., 2012). As a consequence, people with high MA are more likely tp drop out of elective mathematics classes and avoid pursuing careers that require quantitative skills (Ashcraft, 2002; Ashcraft and Faust, 1994; Devine et al., 2012).
Evidence suggests that MA is a distinct construct from other types of anxiety such as test anxiety (TA) and generalized anxiety (GA). TA is defined as anxiety elicited specifically by evaluative situations in educational settings (Hembree, 1988; von der Embse et al., 2018). On the other hand, GA is not specific to particular situations and it reflects an individual's disposition to experience worry (Hill et al., 2016). Moderate correlations have been found between measures of MA and measures of TA (Devine et al., 2012; Dew and Galassi, 1983; Hembree, 1990) and measures of GA (Hill et al., 2016). However, measures of MA correlate more with one another than with measures of TA (Dew and Galassi, 1983; Hembree, 1990) and the correlation between MA and maths performance persists when controlling for TA (Devine et al., 2012). In the case of GA, when scores on GA scales were partialled out from the correlation between measures of MA and maths perfomance, the negative correlation between MA and maths performance persisted in secondary school pupils (Hill et al., 2016). These results suggest that MA is indeed an independent construct specific for maths-related situations and stimuli.

1.5.1 The relationship between MA and performance

The negative correlation between MA and maths performance has been reported by numerous studies (Ashcraft, 2002; Devine et al., 2012; Hembree, 1990; Jansen et al., 2013; Ma, 1999). Whether MA is a product of poor maths performance or whether maths performance is negatively influenced by MA, has been object of debate. Two theories have been developed to explain such relationship (Carey et al., 2016).

The *Deficit Theory* theorizes that having poor maths skills, especially in early childhood, contributes to developing MA (Carey et al., 2016). Supporting this theory are studies that found that children with specific learning disabilities report higher levels of MA compared to normally developing children (Passolunghi, 2011; Rubinsten and Tannock, 2010). Further, adults with poor basic numerical skills report higher MA (Maloney et al., 2011). A criticism to these studies is that the incidence of maths learning disabilities cannot explain the entirety of the extent of MA reporting (Devine et al., 2013). Regarding studies with adults, they lack specificity on the developmental trajectory, providing no information on the direction of the relationship (Carey et al., 2016). Other studies in support of the Deficit Theory reported correlations between students' academic performance and MA levels the following year (Ma and Xu, 2004).

The *Debilitating Anxiety Model* proposes that MA impacts performance by impairing processing resources necessary to efficiently perform maths (Carey et al., 2016; Douglas and LeFevre, 2018). One possibility is that MA taxes on WM functions. Ashcraft and Kirk (2001) found a negative correlation between levels of MA and WM span. Moreover, in problems with high or low WM load, performance to high WM load problems was more affected by MA (Ashcraft and Krause, 2007). Evidence of the influence of MA on executive functions is also provided by the observation that performance improves in situations where cognitive interference is reduced (Faust et al., 1996). A second possibility is that MA determines the selection of less efficient problem solving strategies, resulting in poorer performance (Beilock and DeCaro, 2007). Further support for the Debilitating Anxiety Model comes from studies in which the manipulation of anxiety modulates maths performance (Marx et al., 2013; Seitchik et al., 2014).

Both the *Deficit Theory* and the *Debilitating Anxiety Model* give a theoretical explanation of the relationship between MA and performance, assuming a negative correlation between the two constructs. However, if anxiety has evolved as an adaptive response to threat, can a certain degree of MA be adaptive? Specifically, can a certain level of anxiety-enhanced perceptual processing aid maths performance? Some studies suggest that the effect of MA on performance is mediated by other factors such as negative attitude towards mathematics (Ashcraft, 2002), WM capacity (Beilock, 2008; Mattarella-Micke et al., 2011) and gender (Devine et al., 2012; Hembree, 1990). Some of these studies have reported cases in which MA had limited, if any at all, impact on performance. For example, Mattarella-Micke et al. (2011) reported no correlation between MA and maths performance in individuals with low WM capacity. Betz (1978) found no detrimental effects of MA on maths achievement of males enrolled in a non-maths heavy subject. On the other hand, Devine et al. (2012) showed that girls' maths performance was not affected by MA when controlling for test anxiety. While these studies suggest that MA does not necessarily impact performance, evidence of a positive correlation between performance and MA is lacking. There may be several explanations of why this is the case. The adaptiveness of anxiety is determined by the evolutionary advantage of perceptual enhancement, physical preparation and attentional modulation in the face of possible danger. In practical terms, anxiety is adaptive when a fight-flight-or-freeze response is evolutionary advantageous. However, educational or testing scenarios where MA is likely to develop may not present the characteristics in which anxious arousal is advantageous. It is however to be noted that the literature investigates LMAs or HMAs populations, hardly taking into account intermediate levels of MA. Hence, the lack of positive correlations between MA and performance might origin from a bias in sample selection. It would be interesting investigating whether mild anxious arousal might actually enhance maths performance. It is possible that differences in coping mechanisms and differences in attitude towards mathematics would mediate the relationship between mild anxious arousal and maths performance. For example, individuals that experience moderate feeling of tensions but have a positive attitude towards maths would benefit from physiological arousal. The possibility of positive effects of moderate MA over performance has been overlooked and needs further investigation.

1.5.2 Physiological measures of MA

As for other main types of anxiety, physiological measures of MA have received scientific interest in the past years. However, the literature is still relatively scarce and findings are far from being exhaustive. The big number of measures and indices that can be investigated, the recent interest of psychophysiology in MA and the difficulty in carrying out psychophysiological work in educational settings make this topic still of niche interest. [3]

Autonomic measures and cortisol

The first study that used simple HR (calculated in beats-per-minutes) to investigate MA was Dew et al. (1984). The study focused on whether in test-like situations MA interfered with performance. They assessed the relationship between MA and performance in relation to physiological arousal and avoidance behaviour. Self-report data were collected by asking participants to complete the following questionnaires: the Mathematics Anxiety Rating Scale (MARS, Richardson and Suinn, 1972), the Mathematics Anxiety Scale (MAS; Fennema and Sherman, 1976), and the Anxiety Toward Mathematics Scale (ATMS; Sandman, 1979). During the testing, the participants solved 20 arithmetic computation problems and 15 words problems with no time limits. Subsequently, a third set of problems was administered under test-like conditions: the need for speed and accuracy was emphasized, the task was timed, and it was communicated that the aim was to assess maths ability. The problems in the third set were most likely arithmetic problems, although no clear description of the task is given in the paper. HR was uncorrelated to most self-report measures with the exception of a negative correlation with the ATMS. Such correlation is isolated and not supported by further research.

Two other studies have found little sensitivity of HR to MA levels. In a study (Hopko et al., 2003b) in which anxiety was induced by means of carbon dioxide inhalation (CO2),

[3]This section has been published as part of the book chapter Avancini and Szűcs (2019)

HR increased as a result of the experimental manipulation but there was no difference in physiological response between high maths-anxious individuals (HMAs) and low maths-anxious individuals (LMAs). The study suggests that the manipulation of anxiety by CO2 administration does not influence HR in HMAs more than non-clinical participants. It is however also possible that HMAs do not specifically respond to inhalation of CO2, at least no more than any other population.

Finally, Hopko et al. (2005) found that differences in MA self-ratings to the Abbreviated Maths Anxiety Scale (AMAS, Hopko et al., 2003a) did not correspond to differences in HR modulation when participants were asked to perform attentional tasks. While these attentional tasks mostly included tasks unrelated to performing maths (such as the Stroop task), they did include the PASAT-C (Lejuez et al., 2003) which requires one to perform mental additions. Again, HR after the completion of the PASAT-C was not modulated by pre-experimental levels of MA. Similarly to HR results, little evidence shows that skin conductance is sensitive to MA levels. In the experiment of Dew et al. (1984) described above, data on skin conductance was obtained for two indices: skin conductance fluctuations and skin conductance levels. The first reflected the rate of spontaneous skin fluctuations per minute which occur as a result of the activity of the sudorimotor nerve. Increased nerve activity increases the number of sweat glands opening. Because the activity of the sudorimotor nerve is thought to reflect sympathetic arousal, fluctuations of skin conductance may reflect anxious responding (Bach et al., 2010). The second index, was obtained by comparing the value of post-test skin conductance to a pre-test baseline value. Higher levels of skin conductance post-test would reflect stronger anxious responding during the testing. Only skin conductance levels correlated with scores to the MARS and the ATMS, suggesting that participants with high MA have higher skin conductance during testing than during a baseline period. While these results suggest the sensitivity of skin conductance levels to maths anxious responding, no other study supported these findings. For example, a group of participants that had anxiety induced by the inhalation of CO2 showed increased skin conductance levels compared to than the control group. However, no differences were found between HMAs and LMAs (Hopko et al., 2003b). Furthermore, pre-experimental MA levels assessed with the AMAS did not modulate the skin conductance response during attentional tasks (Hopko et al., 2005).

A third physiological measure that has been traditionally used to assess anxious arousal and that researchers have tried to study as a potential physiological measure of MA, is the concentration of salivary cortisol. The comparison between the concentration in samples collected before and after a stressful event provide a measure of anxious arousal. Salivary cortisol has been found to be associated with maths performance as a function of MA and WM capacity (Mattarella-Micke et al., 2011). Participants judged the correctness of arithmetic problems in the form "x $\equiv$ (y mod z)". Problems had two levels of difficulty: high demand and low demand. The first type included a carry and could not be solved with simple heuristics, while the latter included no carry and could be solved with simple heuristics. Then, WM capacity was assessed with the automated Reading Span task (RSPAN; Conway et al., 2005) which requires one to read a series of sentences followed by a letter and to judge whether the sentences make sense or not. After two to five sentences, the participants were asked to recall as many letters at the end of the sentences as possible. Scores were calculated on the total numbers of letters recalled. Finally, MA was assessed with the shortened MARS (sMARS; Alexander and Martray, 1989). Cortisol samples were taken prior the testing and after the arithmetic task. With increasing levels of cortisol, maths performance decreased when high-WM participants were also HMAs, while performance increased when they were also LMAs. On the other hand, maths performance did not vary as a function of cortisol and MA in low-WM participants. This suggests that the effect of physiological arousal on maths performance depends on the interacting effects of MA and WM capacity and on the difficulty of the task. Such relationships emerged when the operations presented were high demand and not when the operations were low demand. The study provides an indication of the potential of cortisol as a measure of anxiety in maths-related context when WM and task difficulty are also taken into consideration.

The association between salivary cortisol levels and maths performance as a function of MA was also reported by Pletzer et al. (2010). They tested the association between cortisol concentration levels and MA during statistics examinations. In particular, participants were categorized into cortisol profiles according to the variation of cortisol levels pre and post examination compared to a baseline. Only participants whose cortisol levels increased pre-examination and decreased post-examination showed a negative correlation between MA levels (assessed with the MARS30-brief; Suinn and Winston, 2003) and maths performance. The authors argued that examination-induced cortisol responses facilitate the association between MA and maths performance. Both the results of Pletzer et al. (2010) and Mattarella-Micke et al. (2011) suggest that the interaction between MA as assessed by self-report measures, salivary cortisol and performance depends on the interaction between these factors rather than their individual contribution.

Cortisol has also been found to be sensitive to MA levels when the performance of maths is associated with emotional processing (Sarkar et al., 2014). The authors looked at reductions of cortisol levels in a study in which the dorsolateral prefrontal cortex, area associated with emotional processing, was stimulated in order to inhibit negative and facilitate positive emotions by means of transcranial direct stimulation. A dissociation between HMAs and

LMAs was found: in HMAs, reductions in cortisol levels (calculated by subtracting prestimulation from poststimulation levels and then dividing by prestimulation levels) occurred only during real stimulation, while for the LMAs greater reductions in cortisol levels occurred only during sham stimulation.

To date, findings on simple HR and skin conductance point toward a lack of sensitivity of these measures to MA levels as assessed by self-report measures. On the other hand, literature examining cortisol responses seem more promising. In particular, cortisol seems to play a role in the relationship between MA and maths performance. However, the mechanisms through which cortisol, MA and performance interact are still unclear, as the literature is still scarce and mostly correlational.

Electroencephalography

Electroencephalography (EEG) records the spontaneous electrical activity produced by groups of neurons firing in synchrony. Event-related potentials (ERPs), refer to the brain's electrical response time-locked to the presentation of a stimulus (Fig. 1.6). ERPs waveforms consist in *components*, which are deflections characterized by peaks. Peaks have a certain polarity (positive or negative), a latency (how many milliseconds after the presentation of the stimulus the peak occurs) and a location on the scalp where they are detected. Different components are thought to reflect the allocation of brain resources in order to precess stimuli and are considered a correlate of different cognitive processes engaged in such processing.

The P2 component is a positive deflection peaking at around 200ms after stimulus onset. Several studies have found it to differ between levels of MA. For example, is was modulated by MA in a study investigating the precision of magnitude representation (Núñez-Peña and Suárez-Pellicioni, 2014). In a number comparison task (Núñez-Peña and Suárez-Pellicioni, 2014), the P2 amplitude was larger in HMAs than in LMAs when comparing trials in which the numerical difference between the stimuli was small to trials in which the difference was large. Similarly, it was larger in HMAs than in LMAs when comparing trials with small numbers to trials with large numbers. According to well-established research in maths cognition, the processing of arithmetic problems with large solutions is harder than the processing of problems with small solutions (Groen and Parkman, 1972) because large numbers are represented more vaguely and therefore are more difficult to discriminate (Restle, 1970). Furthermore, the comparison between numbers that are numerically close to each other is harder than the comparison of number further apart because the representations of close numbers overlap (Moyer and Landauer, 1967). Both these effects have been attributed to the ability of accessing magnitude representations. The P2 had previously been identified as a measure of effort to distinguish two overlapping number representations as it had been shown that its amplitude is greater when the difference between two numbers is smaller (Szűcs and Soltész, 2008; Temple and Posner, 1998). Hence, the increased P2 amplitude in the HMAs group may reflect less precise magnitude representation which may result in recruitment of more cognitive resources in order to perform the task.

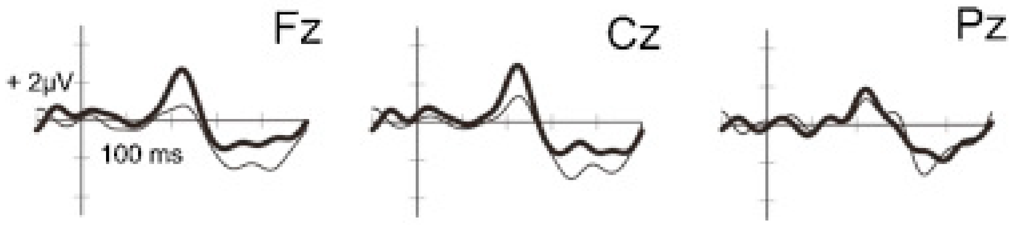

Figure 1.6 Example of an ERP waveform. Depicted here is the P2 component analysed in Núñez-Peña and Suárez-Pellicioni (2014). The P2 peaks at 200ms after stimulus onset and has positive polarity.

Larger prefrontal P2 amplitude in HMAs compared to LMAs has also been recorded in a multi-digit verification task (Suárez-Pellicioni et al., 2015). The prefrontal P2 amplitude has been found to be greater after the presentation of emotionally negative stimuli, and it has been suggested to be a correlate of the employment of attentional resources toward negative stimuli (Carretié et al., 2004, 2001). The authors argued that enhanced P2 amplitude in HMAs may reflect the mobilization of attentional resources toward difficult arithmetic operations which are attributed negative emotional value.

While increased P2 amplitudes have suggested that HMAs allocate more attentional resources when performing tasks involving maths, contrasting results were reported by Klados et al. (2015) in a study using a verification task. While the authors did not specifically refer to the P2 components, the frontocentral positive amplitude around 180–220 ms poststimulus was bigger for LMAs than HMAs. Because a similar effect of MA was found in a control attentional task, the authors suggested that there was more cortical activation in LMAs than in HMAs and this effect seemed to be linked to general WM skills. As noted, while other studies have suggested that the MA effect on the P2 may show that HMAs allocate more attentional resources toward maths stimuli (Núñez-Peña and Suárez-Pellicioni, 2014; Suárez-Pellicioni et al., 2015), Klados et al. (2015) suggest instead that LMAs are spontaneously allocating more resources than HMAs when performing maths. It is still necessary to clarify whether these conflicting results are simply inconsistent or whether they reflect different processes, such as resources availability versus abnormal resources allocation.

Another component that may be sensitive to MA levels is the P3b, which is a positive deflection peaking around 300ms after stimulus presentation with temporal/parietal topography (Polich, 2007; Verleger et al., 1994). It is considered to be sensitive to attentional resources allocation and memory processing (Polich, 2007). For example, in demanding tasks that require more attentional resources or with high memory load, the P3b has smaller amplitude and later latency than in undemanding tasks (Bailey et al., 2016; Kok, 2001). In an arithmetic verification task, HMAs had longer P3b latencies during the processing of large-split solutions at parietal sites. Furthermore, a positive correlation was found between latency and the sMARS scores for large-split solutions. Because P3b latency, as well as longer RTs, is thought to reflect stimulus evaluation time (Polich, 2007) the study suggests that higher MA is reflected in a higher need of engaging attentional resources in order to perform arithmetic (Suárez-Pellicioni et al., 2013a). Similarly to the P2, a positive deflection between 380–420ms was found to be more positive in HMAs than in LMAs (Klados et al., 2015), which is in contrast with Suárez-Pellicioni et al. (2013a) findings. However, the frontocentral topography of such positive deflection compared to the parietal topography of the P3b suggests that the two components may represent different processes.

Other components have been studied as possible correlates of MA. However, such components have been investigated by single studies and therefore only provide anecdotal evidence. Suárez-Pellicioni et al. (2013b) looked at the error-related negativity (ERN) and the correct-response negativity (CRN) to assess whether HMAs showed abnormal error monitoring during the performance of an arithmetic task. The ERN and CRN were selected as components of interest as they have been found to reflect error monitoring. The ERN is a frontocentral negative component peaking around 50–100ms after an erroneous response has been given (Falkenstein et al., 1991; Gehring et al., 1993; Yeung et al., 2004). It has been observed that subjects diagnosed with anxiety disorders show bigger ERN (Luu et al., 2000), suggesting that increased subjective sensitivity to errors produce enhanced ERNs (Vidal et al., 2000). The CRN is a similar negativity to the ERN but elicited after correct responses (Cordes et al., 2001). Studies on other anxiety disorders such as obsessive-compulsive disorder have reported that abnormal error monitoring in anxious participants was not reflected in behavioural measures, but rather in electrophysiological data (Endrass et al., 2010; Gehring et al., 2000; Hajcak et al., 2004). Hence, MA effect on the ERN and the CRN would reflect abnormal error monitoring regardless of any compensation that my result in no behavioural effect. In a numerical Stroop task and a classical Stroop task in which the physical characteristics of the stimuli could match or mismatch the semantic information of the stimuli (e.g. deciding which one between 4 and 2 is the bigger number in the numerical Stroop task; naming the colour of the word “red” when written in green ink in a classical Stroop task), HMAs showed enhanced ERNs in the numerical compared to the classical Stroop task. Furthermore, to assess the difference in processing errors and corrected answers, a difference wave was obtained by subtracting the CRN from the ERN. The MA groups differed in the numerical Stroop task only. Finally, the higher the self-reported levels of MA with the sMARS, the more negative the ERN and the bigger the difference wave amplitude. Hence, the ERN and CRN may suggest that HMAs show abnormal error monitoring that is specific to numerical stimuli.

The P1, the N450 and the conflict sustained potential (Conflict-SP) were investigated to look at whether MA yields abnormal cognitive control when conflicting information is presented as a result of poor attention inhibition (Suárez-Pellicioni et al., 2014). Indeed, these components were selected as they are sensitive to conflict processing. The P1 is a positive wave peaking around 100ms after stimulus onset. It is thought to be a correlate of the processing of low-level stimuli features (Zhu et al., 2010). The N450 is a frontocentral negativity peaking around 450ms after stimulus onset. It is considered to represent the detection of conflicting stimulus information (Szűcs and Soltész, 2012). For example, it has been found to be elicited in the incongruent condition in a numerical Stroop task (Szűcs et al., 2009). The Conflict-SP is a positive wave following the N450 and it has been found to be modulated by conflict level (Lansbergen et al., 2007). In a numerical Stroop task, these components of interest were analysed by grouping the trials according to whether the previous trial was congruent or not. The N450 and the Conflict-SP, but not the P1, differed between HMAs and LMAs (groups selected using the sMARS), showing that the interference of a previous incongruent trial impacts HMAs more than LMAs participants.

Several ERP components have been investigated in relation to MA. However, the literature is still too limited to allow for any satisfactory conclusion on electrophysiological correlates of MA. Overall, the positivity peaking around 200 milliseconds after stimulus onset seem to be the components that most consistently showed a difference between HMAs and LMAs (Klados et al., 2015; Núñez-Peña and Suárez-Pellicioni, 2014, 2015; Suárez-Pellicioni et al., 2013a). This component is thought to reflect attentional resources allocations and memory processing, possibly influenced by emotional value of the stimulus (Carretié et al., 2004, 2001). This might suggest that MA bears an impact on attentional and memory resources. Furthermore, the positivities around 200 and 400 ms found in Klados et al. (2015) have been associated to the relation between MA and memory as well. It is however still to be clarified whether such positivites are generated by the same cerebral structures and induced by the same cognitive functions as those found in other studies.

Finally, it should be noted that comparisons between groups have been done on the basis of groups that had been previously selected with self-report measures. Therefore, the presence or absence of electrophysiological differences between HMAs and LMAs might be related to covert characteristics of self-report questionnaires. The limited literature, the variety of components investigated and the dependency of electrophysiological results to self-report questionnaires calls for replication of the available findings and further research on the topic.

Functional magnetic resonance imaging

fMRI studies have mainly focused on investigating whether HMAs and LMAs differed in the activation of brain areas associated with emotional processing and the anxious anticipation of maths. In anticipating the execution of a maths task, HMAs seem to activate brain areas linked to cognitive control, emotional processing and pain processing. When HMA participants (selected with the sMARS) anticipated an arithmetic verification task, better performance was associated with more activation of bilateral inferior frontal junction and the bilateral inferior parietal lobe (Lyons and Beilock, 2012a). These areas are thought to be involved in cognitive control (Brass et al., 2005) and regulation of emotions (Bishop, 2007). Therefore, it is suggested that for HMAs better performance is associated with increased recruitment of areas linked to cognitive control and emotion regulation when anticipating a maths task. Moreover, the activation of the pain network such as the bilateral dorso-posterior insula and the mid-cingulate cortex before task execution was found to be positively correlated to sMARS scores in HMAs. The authors argued that anticipatory anxiety of maths simulates pain in HMA individuals (Lyons and Beilock, 2012b).

Activity of the default-mode network (DMN) has also been found to differ between levels of MA (Pletzer et al., 2015). Decrease in deactivation of the areas of the DMN has been linked to emotional processing and it has been found to be proportional to the increase of cognitive control (Greicius et al., 2003). In the context of MA, differences due to MA levels (assessed using the MARS30-brief; Suinn and Winston, 2003) emerged in the precuneus during a number comparison task and in the anterior cingulate gyrus during a number bisection task. In the number comparison task, trials could either be unit-decade compatible where the smaller numbers also had the smaller unit digit (e.g. 23 vs. 68) or unit-decade incompatible where the smaller number had the bigger unit digits (e.g. 28 vs. 63). LMAs activated the left inferior frontal gyrus and insula, the left dorsolateral prefrontal cortex, and the supplementary motor area more during incompatible items than compatible items, while HMAs did not. The study suggests that MA is associated with less deactivation of the DMN when inhibitory control is required, such as with incompatible items in arithmetic tasks, highlighting poorer cognitive control in HMAs.

The activity of areas supervising emotion regulation have been found to be modulated by MA in children as well. Young et al. (2012) tested whether children with high MA showed hyperactive amygdala activity during maths problem-solving and stronger connectivity between the amygdala and prefrontal cortex. These regions and structures were chosen because they have been found to be activated during the view of negative stimuli (Sabatinelli et al., 2011) and therefore enabled investigation into whether numeric stimuli were perceived as negative by HMAs in developmental age. Children aged 7 to 9 were administered the Scale for Early Mathematics Anxiety (Wu et al., 2012). Participants took part to two fMRI testing sessions in which they had to perform an arithmetic verification task. Activation in the right amygdala and anterior hippocampus was stronger for HMAs than LMAs. On the contrary, HMAs showed less activation in the intraparietal sulcus, right dorsolateral prefrontal cortex (right dlPFC), and the bilateral caudate and putamen nuclei of the basal ganglia. Moreover, greater deactivation of the ventromedial prefrontal cortex was seen in HMAs. Finally, the authors used connectivity analysis aimed at identifying whether HMAs and LMAs differed in how the amygdala interacts with other brain regions. Compared to LMAs, HMAs showed greater connectivity of the right amygdala to regions associated with social and general anxiety such as the left amygdala, the ventromedial prefrontal cortex and the anterior thalamic nucleus. On the other hand, they showed less connectivity between the right amygdala and the posterior parietal cortex.The study suggests that differences in brain activation associated with different levels of MA are apparent as early as in 7-to-9-year-old children. Specifically, limbic areas were more activated in HMAs. Parietal, prefrontal and basal ganglia were less activated in HMAs. Ventromedial prefrontal areas were instead more deactivated in HMAs. Finally, MA also modulated the connectivity of the right amygdala to adjacent areas of the brain.

Similarly to EEG literature, studies investigating brain correlates of MA through fMRI are still scarce. Overall, the focus has been drawn toward brain areas linked to emotional processing and cognitive control. However, findings should be interpreted with care considering some methodological aspects of the studies reviewed. One issue concerns the study by Lyons and Beilock (2012a), in which better performance was associated with more activation of areas involved in cognitive control when anticipating a maths task. In the study, performance was defined as in terms of "maths deficit", namely the difference in performance between an arithmetic verification task and a word task: the smaller the difference in performance between the two tasks, the smaller the "maths deficit" as a result of better cognitive control. First, such an approach is problematic because the outcome is dependent on not only an impairment in maths but also linguistic task ability. Further, the score can also be interpreted as a "verbal advantage" score and in that case, for example, it could be argued that the identified brain areas reflect happiness about executing verbal rather than mathematical tasks. A second point of concern is that in Lyons and Beilock (2012a,b), the analysis is based on double dipping, a practice in which the data are first analysed to select a subset of significant data and then those data are reanalysed to obtain results. This practice constitutes a circular process in which the assumption of independency of the data is violated and therefore the results distorted (Kriegeskorte et al., 2009). In Lyons and Beilock (2012a), the authors identify brain areas which showed activity correlated with maths deficit scores in HMAs only. After this they tested these brain areas for significant MA effects. Provided that the areas were pre-selected by a significant association defined by the HMAs group, this clearly constitutes invalid double dipping. A similar procedure was used in Lyons and Beilock (2012b). It is important to note that the selected regions are consistently called regions of interest which usually implies that regions are defined before the analysis is run. However, in this case it is clear that regions of interest were defined during analysis and they cannot be considered independently defined.

Overall, the most reliable fMRI findings concern an increased and possibly dysfunctional emotional processing as shown by hyperactive limbic areas (Young et al., 2012) and impaired cognitive control as shown by a reduced deactivation of the DMN in MA participants (Pletzer et al., 2015). Importantly, these studies will need replication before any strong conclusion can be drawn on the implication of these areas in MA cognitive functioning. A final issue on fMRI studies is the interpretation of the imaging data in terms of differences in specific cognitive processes between HMAs and LMAs, which constitutes a case of inverse inference. Inverse inference is a backward reasoning in which the engagement of a cognitive function is inferred by the activation of a specific brain area. However, this type of inference can only be drawn with relative confidence if the region is activated selectively for one specific cognitive function (Poldrack, 2006). Given that several cognitive processes are engaged during arithmetic tasks (Avancini et al., 2015), specific claims about differences in cognitive functioning between MA groups should be specifically tested in the future.

1.5.3 The relevance of physiological measures of MA

Physiological measures have been used to investigate anxiety in the specific case of MA. Differences in physiological arousal between participants with different anxiety levels have been reported. However, the literature is still scarce and only a limited number of physiological indexes have been investigated. Not surprisingly, not all measures reported in this introduction have been used for the present research. However, the knowledge available in the specific field of MA with the broader breath of information available on anxious physiological arousal informed on what specific indexes may have been appropriate to address the specific research questions posed in the present thesis.

1.6 Summary

WM is a system involved in many complex cognitive processes, including maths problem solving. Great interest has been shown for understanding the functioning of a system so central to human cognition. Several models have linked WM to attentional and executive process, which a significant body of literature has identified as the gateway through which anxiety affects performance at cognitive tasks. Furthermore, the intertwined nature of WM, physiological responding and task performance makes physiological measures an appealing tool for measuring MA.

1.7 Overview of the work completed and methodological considerations

The experimental work carried out is centred on the relationship between WM processes and anxiety. The overarching research question is how anxiety affects WM and how physiological measures can inform on such relationship. The case of MA is taken as specific model given the importance of WM in maths processing.

Both frequentist and bayesian statistical analysis have been run and the interpretation of the data has been done taking into account both information. To keep consistency across chapters, bayesian factors have been calculated against the null hypothesis (BF_{01}). The interpretation of the BFs followed the one suggested by Jeffreys (1998). BFs and their interpretation are reported in table 1.1. Furthermore, published pipelines have been used for EEG preprocessing and conservative approaches have been preferred. Finally, I aimed at appropriate statistical power, although methodological difficulties have made it at times challenging to achieve with the available resources. Where appropriate, such methodological issues are discussed in the relevant experimental chapters. Each experimental chapter is composed of its own introduction, methods, results, discussion and conclusions sections.

Chapter 2 focuses on the role of attentional processes in memory encoding. The work is centered on the prestimulus subsequent memory effect originally observed by Otten et al. (2006). In the original paper, this effect has been interpreted as semantic. I hypothesize that such effect may instead reflect attentional processes. If that was the case, the prestimulus subsequent memory effect may allow us to investigate how anxiety may affect WM in its anticipatory component, namely even before stimulus presentation. To address this question I have combined a replication of the experiment run by Otten et al. (2006) with a novel paradigm that had the aim of isolating attentional processes while maintaining as many features as possible comparable to the replicated experiment. ERPs methodology was used to investigate the question.

Chapter 3 looked at the effect of anxiety on VSWM, taking a resource model perspective. In this study, a delayed-detection paradigm was run while anxiety was experimentally manipulated. Anxiety modulation was obtained with a modified version of the NPU-threat of shock protocol (Schmitz and Grillon, 2012). The measure of anxiety chosen was the startle reflex recorded with ocular EMG. Maximum likelihood estimation was run on behavioural data to obtain the estimates of the models on which statistical inference was carried out.

Chapter 4 constitutes the last experimental chapter. The experiment focuses on how physiological measures can be used to detect MA. To this aim we tried to replicate Rubinsten et al. (2012)'s experiment while recording physiological measures. The paradigm combined an affective priming task with an arithmetic verification task. The measures chosen were the startle and HRV indices.

Each chapter has a detailed discussion of the single experiment and chapter 6 will discuss overall implications of the present work. While carrying out my PhD research, I possibly came to face issues related to the replication crisis (Colling and Szűcs, 2018; Pashler and Harris, 2012). Such issues are elaborated in the general discussion in light of the present experimental work.

BF_{01}	**Interpretation**
> 100	Decisive evidence for H_0
30-100	Very strong evidence for H_0
10-30	Strong evidence for H_0
3-10	Substantial evidence for H_0
1-3	Anecdotal evidence for H_0
1	No evidence
0.3-1	Anecdotal evidence for H_1
0.1-0.3	Substantial evidence for H_1
0.03-0.1	Strong evidence for H_1
0.01-0.03	Very strong evidence for H_1
< 0.01	Decisive evidence for H_1

Table 1.1 Interpretation of the BF_{01} based on Jeffreys (1998).

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Chapter 2

The prestimulus subsequent memory effect and attentional processes

2.1 Introduction

Anxiety is thought to represent anticipatory expectation of threat. As a consequence of such anticipatory quality, anxiety it is not a psychophysiological response that is merely time-locked to the presentation of a certain threatening stimulus. Rather, it is a sustained psychophysiological activation whose intensity fluctuates over time in response to threat characteristics (Schmitz and Grillon, 2012). Studies looking at the effect of anxiety on WM have generally focussed on maintenance and retrieval and some evidence also suggests an effect of anxiety on memory encoding (Mueller, 1979; Richards and French, 1991). However, a further step back could be taken. Specifically, given that anxiety is sustained over time, it may be hypothesized that its detrimental effects on WM could be detected even before stimulus presentation. If the pre-stimulus subsequent memory effect (psSME) reflected attention allocation, it would provide a starting point to investigate whether anxiety affects the efficiency of WM memory even before a stimulus is presented.

The rationale behind the choice of investigating the psSME in the context of anxiety was driven by the common anticipatory aspect of both attention and anxious responding. Furthermore, attentive processes during encoding modulate memory performance. Hence, the study wants to assess whether the established detrimental effect of anxiety on performance (Eysenck and Calvo, 1992) may be detected early on. Before diving into the specific effects of anxiety, the present chapter aims at establishing whether pre-stimulus attentional processes can predict memory performance in normal adults. To do so, the analysis has focussed on the psSME as originally reported by Otten et al. (2006).

This study was preregistered on Nature Human Behaviour but did not meet the interest of the Editor.

2.1.1 Memory encoding and attentional processes

Memory performance is influenced by attentive processes during encoding. There are several mechanisms through which attention is thought to influence how successfully we encode stimuli and the interaction between attention and memory is still a hot topic in the literature. In the case of WM, it is still debated whether WM and attentional processes are essentially the same mechanism (Awh and Jonides, 2001; Bae and Luck, 2018; Fusser et al., 2011). The fact that different types of attention, as well as dissociable WM systems, have been reported increases the complexity of the interaction between attention and WM. Furthermore, attention may play different roles at different stages of WM processing (Awh et al., 2006; Gazzaley and Nobre, 2012). Nevertheless, it is widely believed that selective attention provides top-down regulation that determines our ability of encoding task-relevant and ignore task-irrelevant stimuli. By selectively attending to stimuli and by inhibiting the access of task-irrelevant information, selective attention exerts an anticipatory redirection of cognitive resources towards target stimuli (Awh et al., 2006; Gazzaley and Nobre, 2012; Myers et al., 2015; Tas et al., 2016). For instance, in attentional blink paradigms, when participants are asked to report two stimuli presented in rapid succession, the processing of the second target is impaired. However, if participants are instructed to ignore the first target, the second stimulus is processed (Raymond et al., 1992). In the case of visuospatial information, when the location of a target item is cued, the features of the target are better remembered than when the target is not cued (Schmidt et al., 2002). However, top-down regulation is not the only way in which selective attention regulates memory encoding. Evidence suggests that the perceptual system can also influence attention bottom-up, determining what stimuli will be encoded in memory. Visual search paradigms have indeed shown that attentional capture facilitates encoding in memory (Awh et al., 2006; Belopolsky et al., 2008).

Attention is also thought to play a key role in encoding into LTM (Blumenfeld and Ranganath, 2007; Kim et al., 2010). While WM and LTM are considered separate systems, successful maintenance of representations in WM is thought to support LTM formation (Khader et al., 2010). Brain areas such as the dorsolateral prefrontal cortex, the occipital cortex and the hippocampus have been found to be activated during WM processes and to predict later recollection (Blumenfeld and Ranganath, 2006; Davachi et al., 2001; Ranganath et al., 2005; Schon et al., 2004). Furthermore, slow event-related potentials during a WM task predicted later recollection, suggesting that WM maintenance contributes to LTM formation and that this may occur through strengthening of stimulus-specific cortical memory traces

(Khader et al., 2007). Hence, given that formation of LTM representations is supported by WM maintenance and that attentional processes determine the items that will be encoded in WM, attentional resources play a key role in LTM encoding.

In addition to stimulus-dependent attentional processes such as selective attention, sustained attention (vigilance) is also required to perform tasks. Sustained attention has been described as the ability of keeping a focus of attention and to remain alert to stimuli over prolonged periods of time (Warm et al., 2008). It has been found not to be constant over time and to spontaneously fluctuate from moment to moment transitioning from optimal to suboptimal states (Esterman et al., 2012, 2014; Mackworth, 1948). During the latter, participants show decreased accuracy, increased variability in reaction times and increased speed-accuracy trade-offs (Rosenberg et al., 2013). Fluctuations in attention have been linked to fatigue and resources overload (Helton and Warm, 2008; Warm et al., 2008) or to mindlessness as a result of task automatization and routinization (Robertson et al., 1997; Smallwood and Schooler, 2006). The spontaneous fluctuations as well as the ability of mantaining sustained attention have been linked with success in memory encoding and maintenance, as suggested by studies on populations with attention deficits or on sleep deprivation (Dennis et al., 2007; Lenartowicz et al., 2014; Yoo et al., 2007).

2.1.2 The prestimulus subsequent memory effect

A phenomenon that has received particular interest in the area investigating memory encoding is the pre-stimulus subsequent memory effect (psSME). Pre-stimulus electro-encephalography (EEG) activity has been shown to predict whether a stimulus will be later remembered or forgotten. The effect was first observed by Otten et al. (2006). In her study, participants were asked to perform a semantic animacy judgement over written words and were later presented with a surprise recognition task. The prestimulus amplitude of stimuli that were later remembered was more negative than prestimulus amplitudes of stimuli that were later forgotten. The psSME has been found both in event-related brain potentials (ERPs) and time-frequency (TF) activity and it has been attributed to encoding processes (Galli et al., 2013; Kleberg et al., 2014; Otten et al., 2006, 2010).

Event-related psSME has often been reported as a left-frontally distributed negative deflection, more negative for later remembered compared to later forgotten stimuli. Such effect has been detected with written words (Galli et al., 2013; Otten et al., 2006, 2010; Padovani et al., 2013), auditory words (Galli et al., 2012, 2013; Otten et al., 2010), and pictures (Galli et al., 2014, 2011). Moreover, encoding strategies (Galli et al., 2012) and executive functions (Galli et al., 2013; Padovani et al., 2013; Richter and Yeung, 2016) have been suggested to modulate ERP psSME. Notably, while these studies have identified psSMEs with similar deflections and topographical distributions, the time windows where the effects emerged varied greatly possibly as a result of methodological choices. It has been suggested that the frontally distributed ERP psSME reflects the activation of a task set optimal for semantically oriented processing (Otten et al., 2006; Pashler et al., 2001), similarly to the left-frontal negativity associated with phonological processing in WM control (Ruchkin et al., 2003). On the other hand, the ERP psSME detected in studies where motivation to remember was experimentally manipulated has shown different characteristics: remembered stimuli were more positive than later forgotten stimuli at parietal(Galli et al., 2014; Gruber and Otten, 2010; Padovani et al., 2011) and frontal (Galli et al., 2011) sites. It has been argued that while the negative psSME may reflect the preparation of semantic processes, the positive psSME may reflect more elaborate associative processes linked to motivation (Galli et al., 2014; Gruber and Otten, 2010).

The psSME is believed not to be generated by general recruitment of attentional resources because it appears only when participants are requested to perform a semantic judgement (Otten et al., 2006). However, recently it has been shown that attentional mechanisms do modulate the psSME (Galli et al., 2013; Padovani et al., 2013). In particular, reducing the available attentional resources prior to stimulus presentation has been suggested to impair encoding and annul the psSME (Galli et al., 2013). While it is not clear what specific functional process contribute to the psSME, it is plausible that the flexible allocation of attentional resources plays a significant role in influencing the preparatory activity prior memory encoding.

Various TF effects in EEG have been attributed to psSMEs. The effect emerges as a positive deflection with higher power for later remembered compared to later forgotten stimuli. Similarly to the ERP psSME, the TF psSME is located over frontal electrodes, although medial temporal psSME have been detected as well (Guderian et al., 2009). Oscillatory psSME has been attributed to a range of different phenomena. It has been suggested that it reflects preparatory processes for the encoding of episodic memory (Addante et al., 2011; Kleberg et al., 2014) and the binding of information interlinked with the stimulus that will be later remembered (Scholz et al., 2017). Frontal theta psSME has also been found to be enhanced when the motivation to attend the stimuli is high (Gruber et al., 2013). Evidence on whether the functional role of the prestimulus theta is linked to voluntary encoding is still mixed. Indeed, it has been detected both when encoding was voluntary (Gruber et al., 2013; Guderian et al., 2009; Kleberg et al., 2014) and involuntary (Addante et al., 2011; Fellner et al., 2013; Salari and Rose, 2016; Scholz et al., 2017). In particular, when the role of prestimulus theta during voluntary and involuntary encoding was specifically assessed (Schneider and Rose, 2016), a psSME emerged only when encoding was voluntary. However, a direct comparison between voluntary and involutary psSME did not reveal any difference. Finally, TF psSME has been detected in other frequency bands such as alpha (Park et al., 2014), beta (Noh et al., 2014; Salari and Rose, 2016; Schneider and Rose, 2016; Scholz et al., 2017), gamma (Noh et al., 2014), and occasionally theta psSME has not been detected (Noh et al., 2014).

The functional roles of ERP and TF psSMEs are debated. While evidence for theta psSME as correlate of top-down control is still mixed and its functional role has not yet been established, theta activity has been linked to attentional resources (Missonnier et al., 2006). Frontal theta synchronisation has been found to be modulated by experimental manipulations that modulate attentional resources. For example, frontal theta synchronization has been shown to increase with task demand (Chander et al., 2016; Mazaheri and Picton, 2005; Sauseng et al., 2007a), increased fatigue (Wascher et al., 2014), the engagement of sustained (Clayton et al., 2015) and divided attention (Keller et al., 2017), and following oddball targets (Jyrki Ahveninen, Samantha Huang, John W. Belliveau, Wei-Tang Chang, 2013; Keller et al., 2017; Mazaheri and Picton, 2005). It is therefore possible that the preparatory processes ascribed to prestimulus theta are functionally attentive. On the other hand, evidence for attentional origins of ERP spSME is still scarce and it relies on the modulation that task demand has on such an effect (Galli et al., 2013). One question is whether the various ERP and TF psSMEs have similar functional roles or reflect different mechanisms (Sauseng et al., 2007b). As this introduction has suggested, one possibility is that effects are related to attentional processes. Another option is that TF psSME underlies preparatory attentional processes and ERP psSME underlies the activation of a task set for semantically oriented processing.

An additional point is the exact replicability of psSMEs. Recently, the question of replicability has received a lot of attention in the whole of cognitive neuroscience (Kappenman and Keil, 2017). One of the threats to reproducible results is statistical power (Button et al., 2013; Ioannidis, 2005; Szűcs and Ioannidis, 2017) and the psSME literature is no exception. Calculating the power for effect sizes (Cohen's d) traditionally considered small (d = 0.2), medium (d = 0.5), and large (d = 0.8) (Cohen, 1962; Rossi and Pourtois, 2015; Sedlmeier and Gigerenzer, 1989) with a significance level of $\alpha = 0.05$, ERP studies have low statistical power (median power to detect small, medium and large effect in ERP studies: 0.16, 0.65, 0.96 (table 2.1).Consequently, variability in the parameters of the ERP psSME can not only be attributed to different design and data analysis parameters but also to low power Szűcs and Ioannidis (2017).

In summary, while ERP findings seem fairly replicable, the literature has some important shortcomings. Firstly, the statistical power of many studies is low. Secondly, ERP timings are very variable across studies. Thirdly, time-frequency findings are very variable in terms of frequencies, locations and timings of effects. While some variability can be attributed to task differences, low power can also lead to highly variable findings. Finally, an important open question about the interpretation of the psSME is whether it reflects semantic or attentional processes. Clarifying the involvement of attentional mechanisms in psSMEs is not only important for theory but it also informs research on memory formation in clinical populations in which memory is impaired.

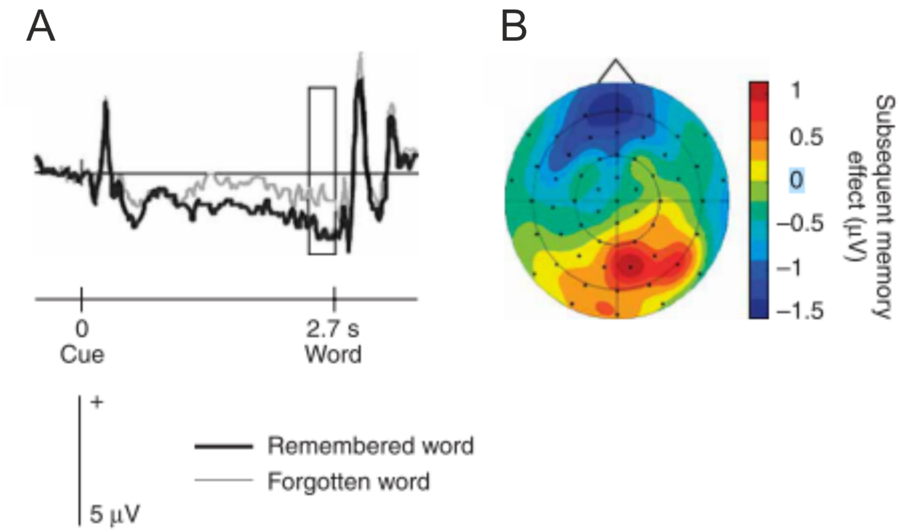

Figure 2.1 Prestimulus activity predictive of encoding success as reported in the original paper of Otten et al. (2006). A) Grand-average of the ERP prestimulus waveform at a representative electrode corresponding to Fp1 of the 10-20 system. B) Topography of the psSME voltage distribution over the whole scalp in the -250ms to 0ms time-window. The effect was obtained by subtracting the voltage of forgotten words to the voltage of remembered words.

2.1.3 Rationale of the study

Here, I aimed at resolving important controversies by replicating ERP findings related to the psSME in a study with very high statistical power. We attempted to replicate the classical incidental encoding task (Otten et al., 2006) used to elicit EEG psSMEs with high statistical power to examine the robustness of the various ERP psSMEs previously reported. The decision of replicating such specfic study came from the fact that Otten et al. (2006) were the first to report the psSME. Given that the focus of the present thesis is on WM, it could be argued that the original task from Otten et al. (2006) is a LTM task. While this is a legitimate concern, WM has been described as the gateway to LTM (Atkinson and Shiffrin, 1971) and processes happening before the presentation of a stimulus can reasonably be assumed to overlap.

Furthermore, the present study has been conducted with a conservative approach with the aim of being as replicable as possible: published data-preprocessing pipelines have been used for bad channel detection and interpolation and no eye-blinks correction has been applied on the data. Finally, I attempted to determine whether effects are related to preparatory engagement of attentional mechanisms or to semantic processes. We achieved this by comparing prestimulus EEG data in later remembered and later forgotten trials in the above encoding task and in high-attention and low-attention trials in a purely attentional task. If psSMEs are elicited by semantic processes, an interaction between task and trial type should be detected.

As reported in this introduction, the psSME has been observed not only in ERPs but also in TF studies. While looking at TF data has great potential of giving insights into the engagement of attentive processes, in the present thesis only ERPs have been analysed.

Study	**N**	**Power** 0.3	0.5	0.8	**Effect size**	**Loc.**	**Timing**
Galli et al. (2011)	15	0.11	0.44	0.82	0.61+ (women-unpleasant)	F	-1200 to 0 ms
Padovani et al. (2011)	21	0.14	0.59	0.93	0.84	F	-1300 to -700 ms
Padovani et al. (2013)	21	0.14	0.59	0.93	0.53 (stay) 0.50 (switch)	F F	-2000 to -1000 ms
Otten et al. (2006)	24	0.16	0.65	0.96	0.79 (semantic)	F	-250 to 0 ms
Otten et al. (2010)	24*	0.16	0.65	0.96	0.59 (written) 0.50 (auditory)	F F	-750 to -250 ms -750 to -250 ms
Gruber and Otten (2010)	24	0.16	0.65	0.96	0.63+ (high reward)	M	-700 to 0 ms
Galli et al. (2012)	26	0.17	0.69	0.97	0.47	F	-500 to 0ms
Galli et al. (2013)	28	0.18	0.72	0.98	0.63+ (auditory-easy) 0.44(easy)	P F	-2200 to -1500 ms -1500 to -500 ms
Galli et al. (2014)	30	0.19	0.55	0.99	0.39+ (unpleasant-detached) 0.38+ (unpleasant-detached)	right CP right CP	-800 to -400 ms -400 to 0 ms

Table 2.1 ERP studies ordered by sample size. The asterisk (*) indicates the median value. Post-hoc statistical power is calculated for Cohen's d of 0.2 (small), 0.5 (medium), and 0.8 (large) with respect to $\alpha = 0.05$ assuming two-tailed matched samples t-tests. Effect sizes (Cohen's d) have been calculated from the *F* and *t* statistics reported in the papers for significant psSMEs. When disambiguation is needed, the condition in which the spSME was significant is reported in brackets. ERP psSME refer to *remembered* being more negative than *forgotten*. The plus sign (+) indicates inverse psSMEs (*forgotten* more negative). Location acronyms are as follows: frontal (F), parietal (P), central (C), and midline (M).

2.2 Materials and methods

2.2.1 Participants

60 native English speaking participants were recruited in Cambridge, UK. 39 (21 F, 18 M) were retained for statistical analysis. Participants had normal or corrected-to-normal vision and no history of psychiatric disorders. The following criteria determined the exclusion of a participant from the analyses: if the participant failed to complete the full testing session; if behavioural performance was lower than 50% in the encoding task and if they fell in the lowest 5% of *d'* scores in the attention task (see subsection 2.2.3); if there were less than 15 artifact-free trials per condition; if on average across blocks there were no more than 25% of channels were interpolated. Participants that failed to meet the inclusion criteria in one of the tasks were excluded from all analyses

Participants were recruited via the University bulletin and paid £20 for their participation. The study was approved by the Psychology Research Ethics Committee of the University of Cambridge.

2.2.2 Tasks and procedure

Stimuli and presentation time were as in Otten et al. (2006) with some modifications. In the encoding and recognition phases stimuli were words (4-10 letters, 1-30 occurrences per million) (Kučera, 1967). In the attentional task stimuli were strings of random letters (4-10 letters). We obtained the list of the words used in Otten et al. (2006) with their respective animacy values as courtesy of Dr L. Otten (see table 2.3 and table 2.4 in the appendix of this chapter). I considered some animacy judgements to be ambiguous (e.g. *ANKLE* and *CABBAGE* were judged as animate). Therefore, from the same database (Kučera, 1967), I selected our own pool of stimuli excluding body parts, plants and fruits (see table 2.5 and table 2.6 in the appendix). The stimuli were displayed on a grey background (RGB [64 64 64]) and white font at the centre of the screen.

The testing session started with the encoding phase as in Otten et al. (2006). 320 words (one occurrence per word) were presented divided into four blocks of 80 words each. Each word was preceded by a cue. There were two cue types: "X" and "O". Within a block, only one cue type was presented. Blocks associated with one cue type were alternate blocks associated with the other cue type. For example, the first and third blocks used "X" and the second and fourth blocks used "O". The order of presentation of the cues was be counterbalanced across participants. Cue types did not have any function in the encoding phase other than serving as fixation point. However, cue type carried task relevant information in the attention task, as it will be explained later in this section when describing the attention task. The decision of keeping the same cues between the two tasks was made in order to reduce perceptual differences between them.

The sequence and timing of events within each trial followed that of Otten et al. (2006). Each trial begun with the presentation of the cue for 2600 ms followed by 100 ms of blank screen. Then, a word was be displayed for 300 ms. Intertrial interval (ITI) consisted of pound signs ("######") which stayed on the screen a random time between 2000 ms and 2200 ms (fig. 2.2 A). As in Otten et al. (2006), participants had to judge whether the word referred to an animate or inanimate object by pressing a button with their left or right index finger. The laterality of response buttons was switched after the second block and counterbalanced across participants. Accuracy and speed were stressed. To reduce artifacts during epochs, participants were instructed to blink only during the ITI.

After the encoding phase, participants performed the attention task which functioned as a distractor task as well (fig. 2.2 C). This task is an original task specifically developed for investigating my research question and was not present in the original paper of Otten et al. (2006). The stimuli presentation was the same as in the encoding phase with the following modifications. Each block consisted of the presentation of 80 strings of letters (320 strings in total, half of them longer than 5 characters) and each block was divided into sequences of 10 and 6 trials. The stimuli within each sequence were preceded by the same cue. The cue indicated whether the participant had to judge whether the non-word presented is longer than 5 letters (*high-attention* trials) or whether the participant simply had to press a button when the stimulus appears (*low-attention* trials). Sequences of 10 trials were always be assigned to the *low-attention* condition and those with 6 will always be assigned to the *high-attention* condition (fig. 2.2 D). At the beginning of each block, the participant was informed of the association between cue type and task type. Such association and the laterality of the response buttons was counterbalanced within the four blocks. The order of presentation of the sequences was randomized across blocks (for example, in the first block the sequences will follow the *high-attention-low-attention* order). The sequence design has been chosen over the traditional oddball task to overcome the possible contamination of prestimulus activity from surprise effects elicited by the cue change.

Finally, a surprise recognition phase followed the attention task (fig. 2.2 B). Succession of events during trials was the same as in the encoding phase with the difference that the cue was an exclamation mark, as in (Otten et al., 2006). The 320 words presented in the encoding phase were presented intermixed with 160 new words (total of 480 words). By button pressing, participants decided whether they had seen the word during the encoding phase and whether they were confident or non-confident about their decision.

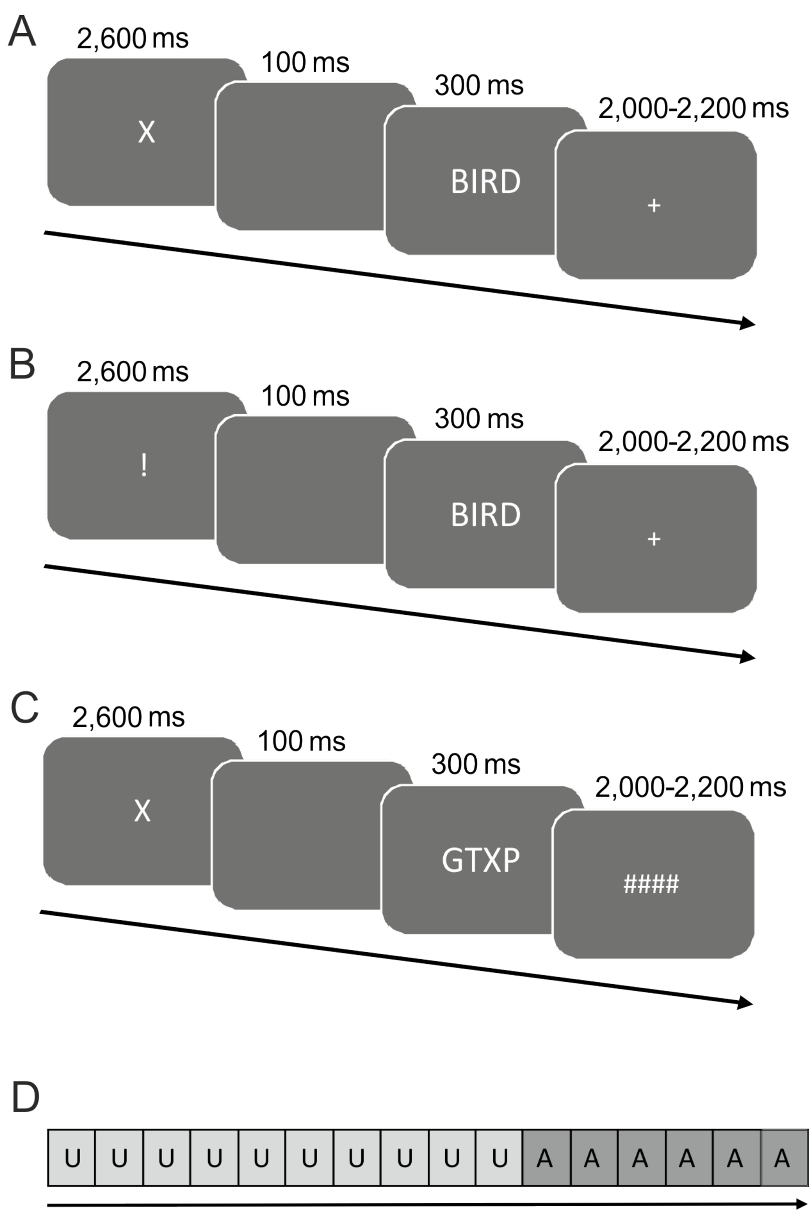

Figure 2.2 Succession of events during trials. Trial structure was the same in the encoding task (A), recognition task (B) and the attention task (C). In the encoding task (A) and attention task (C), there were two types of cue ("X" and "O"). In the recognition task (B), the cue was the same in every trial ("!"). D) Example of sequence succession in the attention task. In this example, a sequence of 10 *low-attention* (*U*) trials is followed by a sequence of 6 *high-attention* (*A*) trials. Each block of the experiment will contain 5 sequences of *low-attention* alternated to 5 sequences of *high-attention* trials.

2.2.3 Behavioural data

In all three tasks, RTs were calculated from the onset of the target word/string. In the attention task, the *d'* was calculated in MATLAB with the following formula (Stanislaw and Todorov, 1999):

```
d' = zscore(targets) - zscore(false_alarms)
```

where `targets` is the accuracy of correctly identified targets in the *high-attention* condition. The accuracy of correctly identified targets was obtained by dividing hits by the total number of targets ($\text{hits}_{targets}/\text{N}_{targets}$). `False_alarms` was obtained with the following formula:

```
false_alarms = 100 - non_targets
```

with `non_targets` being the accuracy of correctly ignored non-targets in the *high-attention* condition. The accuracy of correctly ignored non-targets was obtained by dividing the number of ignored non-targets by the total number of non-targets ($\text{hits}_{non-targets}/\text{N}_{non-targets}$). The function `zscore()` converts each element of the input vector such that the vector values are centred to have mean 0 and standard deviation 1.

Behavioural data were not analysed for hypothesis testing but used for subjects and trials rejection.

2.2.4 EEG data acquisition and pre-processing

Electroencephalography (EEG) data was acquired with 129-Channels HydroCell nets (Electrical Geodesics Inc.) (see fig. 2.3 for whole-head channel locations). The recording took place inside an electrically shielded room at a sampling rate of 500 Hz. Electrode impedance was kept below 50 kΩ.

Bad channel detection was carried out with the PREP pipeline extension (Bigdely-Shamlo et al., 2015) for the EEGLAB toolbox (Delorme and Makeig, 2004) which run automated noise removal, bad channel detection, and robust re-referencing. For each experimental block, the PREP pipeline was run on continuous EEG using default settings. Frequencies multiple of 50 Hz up to the Nyquist frequency (50 Hz, 100 Hz, 150 Hz, 200 Hz, 250 Hz) were removed. Then, the data was re-referenced to the average reference. Finally, a 0.1-20 Hz band-pass filter was applied with the `pop_eegfiltnew()` function in EEGLAB and detrended.

Epochs from -500 ms before cue-onset untill word onset were extracted from continuous EEG. Removed channels were interpolated with spherical interpolation and re-referenced to Cz. Epochs were then rejected if voltage exceeded $\pm 100 \mu V$ using `pop_eegthresh()`.

Epochs were then baseline corrected with the `pop_rmbase()` function using the 500 ms pre-cue baseline.

In the encoding task, epochs were backsorted as *remembered* if in the recognition task they were given a confident recognition judgement and as *forgotten* if they were wrongly judged as new (Otten et al., 2006). Epochs whose corresponding RT was be below 200 ms were be excluded from the analysis. In the attention task, the first trial of each *high-attention* and *low-attention* sequence was be discarded from the analysis to avoid the influence of surprise responses elicited by the change in cue type.

Analyses were first run independently for each task. Then, to assess whether psSME are attentional in nature, the two tasks were compared.

Statistical analysis

ERPs were obtained by averaging epochs from each electrode according to the conditions. Because the psSME was found in the last 250ms of the prestimulus interval, confirmatory analysis were run on the averaged ERPs during the last 250ms. Furthermore, to avoid double-dipping, confirmatory analyses were run only on the the averaged ERPs of electrodes 18 and 22, that are equivalents of Fp1 of the 10-20 system, as used in Otten et al. (2006). Paired t-tests corrected for false discovery rate (FDR) and paired bayesian t-tests were run between *remembered* and *forgotten* trials to attempt to replicate the psSME found in (Otten et al., 2006). The contrast between *high-attention* and *low-attention* trials assessed whether the attention task was successful in distinguishing between attend and low-attention items. Furthermore, the attention effect was compared to the memory effect. Namely, the difference between *high-attention* and *low-attention* was directly compared to the difference between *remembered* and *forgotten* trials. In order to have the same number of trials per condition in the attention task, 5 trials per condition were extracted from each sequence and kept for analysis.

Furthermore, to better assess the location of the psSME and of the attention effect in a novel task, all electrodes in the -250ms to 0ms time-window were tested. This time window was chosen based on the time window in which Otten et al. (2006) detected the psSME. To decrease the likelihood of finding bogus effects, and therefore to increase replicability, a mass univariate approach was adopted (Groppe et al., 2011; Luck and Gaspelin, 2017). Cluster-based permutation analysis was run using FieldTrip toolbox (Oostenveld et al., 2011). As test statistics, paired one-tailed t-tests were used in the individual tasks as the direction of the effect was informed by the results from Otten et al. (2006). At the cluster level, the null distribution was generated using Monte Carlo methods with 1,000 permutations. The p-threshold for significant clusters was set to 0.05 one-tailed. Other settings were kept as default. In the encoding tasks, t-tests were contrasted *remembered* and *forgotten* trials, while in the attention task t-tests contrasted *high-attention* and *low-attention* trials. To compare the two tasks, cluster-based permutation was run using two-tailed t-tests with p-threshold for significant clusters set to 0.025 because the direction of the effect was unknown. We compared the *remembered* to the *high-attention* condition and the *forgotten* to the *low-attention* condition

2.2.5 Results

After preprocessing, participants had on average 64 trials in the remembered condition, 47 trials in the forgotten condition, 54 trials in the high-attention condition and 47 trials in the low-attention condition.

The paired t-tests and bayesian t-test on the average ERP amplitude in the -250ms to 0ms prestimulus time-window was statistically significant for remembered compared to forgotten trials (t(38) = -2.00, $p \leq 0.05$, $BF_{01} = 0.96$) suggesting neither evidence for the alternative nor for the null hypothesis. The t-test comparing high-attention and low-attention trials was not significant (t(38) = -0.79, p = 0.43, $BF_{01} = 4.33$) and 4.33 times more likely to be observed under the null hypothesis. The t-test comparing remembered and high-attention trials (t(38) = -0.31, p = 0.76, $BF_{01} = 5.53$) as well as the t-test comparing forgotten and low-attention trials (t(38) = -0.08, p = 0.94, $BF_{01} = 5.78$) was not significant and the data were likely to be observed under the null hypothesis. The t-test comparing the attention effect to the memory effect was not significant (t(38) = 0.43, p = 0.67, $BF_{01} = 5.31$). Descriptives are reported in table 2.2.

The topography contrasting remembered and forgotten trials (first row - third column of fig 2.5) presents a similar phase reversal reported in Otten et al. (2006) (figure 2.1). On the other hand, the voltage over most of the scalp topography of the attention effect approaches 0 (fig. 2.5).

Testing for an effect in the latency range from 250 to 0 ms pre-stimulus, the cluster-based permutation test did not reveal any significant difference between the remembered and the forgotten condition, nor between the high-attention and low-attention conditions, nor between forgotten and low-attention. This suggests that the data from the contrasted conditions come from the same probability distribution in the last 250ms prestimulus interval. Cluster-based permutation test revealed a significant difference between remembered and high-attention trials ($p \leq 0.05$) in the latency range from 250 to 0 ms pre-stimulus over central-left electrodes (Fig. 2.7).

Encoding task		Attention task	
Remembered	**Forgotten**	**Attended**	**Unattended**
-1.62 $\overline{M}$ 4.82 SD	-0.66 $\overline{M}$ 4.79 SD	-1.33 $\overline{M}$ 6.55 SD	-0.60 $\overline{M}$ 5.12 SD

Table 2.2 Means ($\overline{M}$) and standard deviations (SD) of the voltage in μV averaged within the -250ms to 0ms time-window in the four experimental conditions.

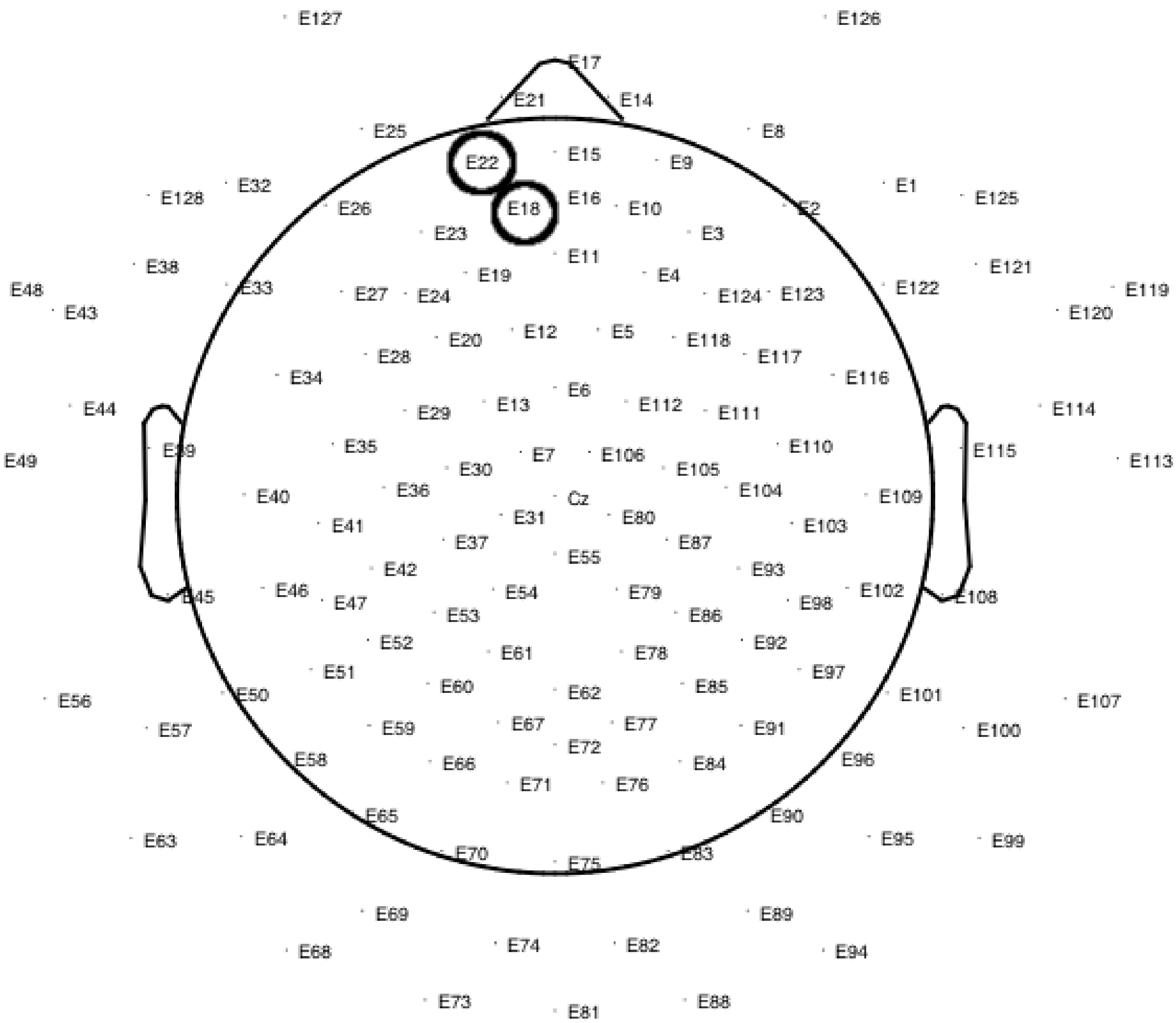

Figure 2.3 Channel locations of the 129-channels HydroCell Geodesic Sensor Net used in the current experiment. The boxes mark the two electrodes used for detecting the pSME and the attention effect.

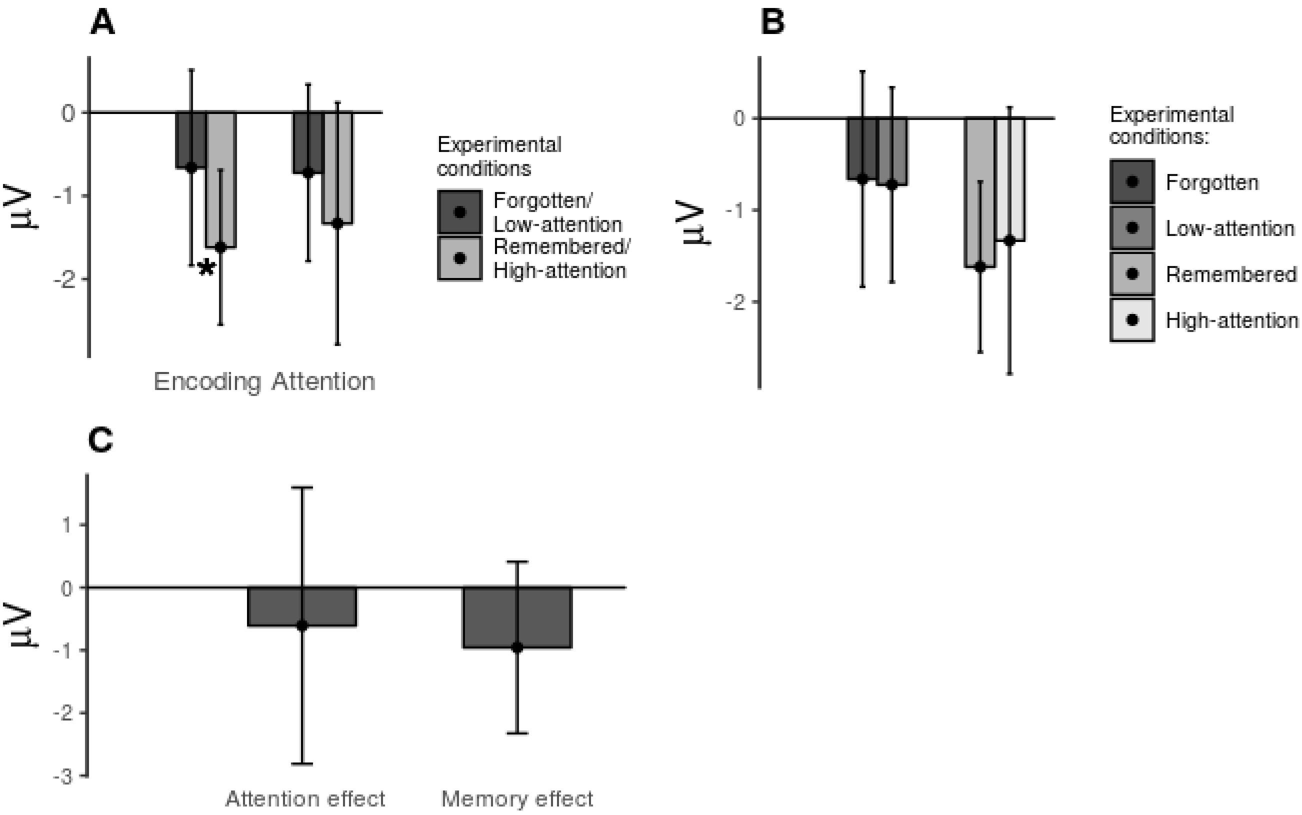

Figure 2.4 A) Quantification of the psSME and the attention effect in the -250ms to 0ms time-window at the frontal-left electrodes analysed. B) Quantification of the contrasts between tasks in the -250ms to 0ms time-window at the frontal-left electrodes analysed. C) Quantification of the contrast between the attention effect (high-attention minus low-attention) and the memory effect (remembered vs forgotten) in the -250ms to 0ms time-window at the frontal-left electrodes analysed. The asterisk (*) denotes $p \leq 0.05$. Vertical bars are 95% confidence intervals.

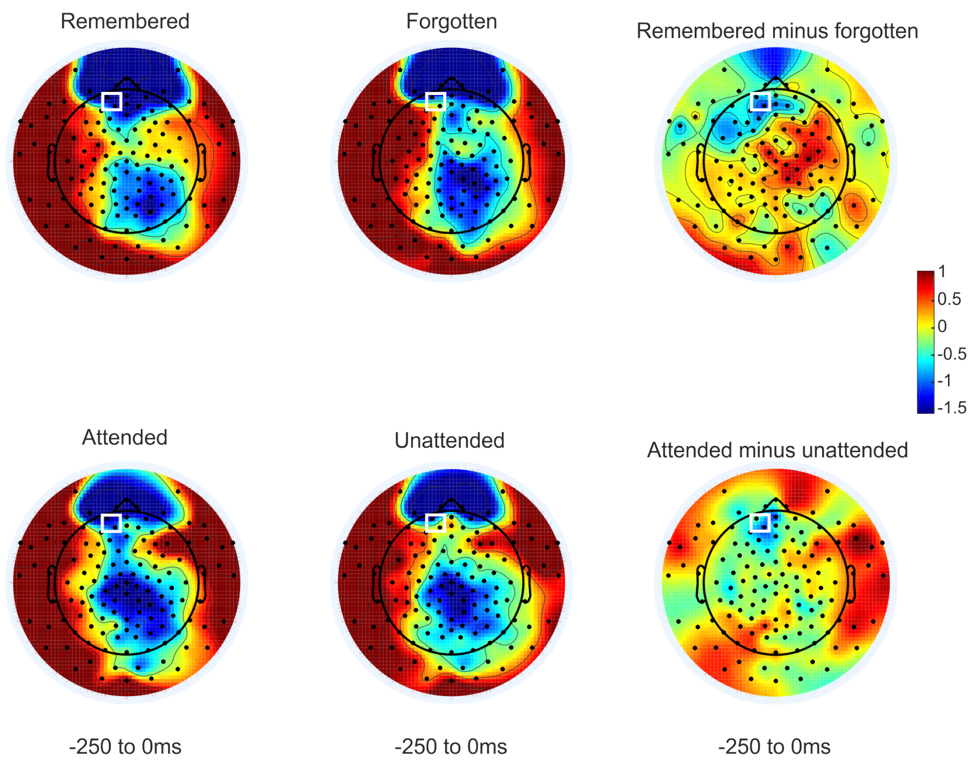

Figure 2.5 Topographies of the voltage over the whole scalp in the -250ms to 0ms time-window. The psSME (third column-first row) has been obtained by subtracting the voltage of *forgotten* trials to the voltage of *remembered* trials. The attention effect (third column-second row) was obtained by subtracting the voltage of *low-attention* trials to the voltage of *high-attention* trials. The white box marks the electrodes selected for analyses.

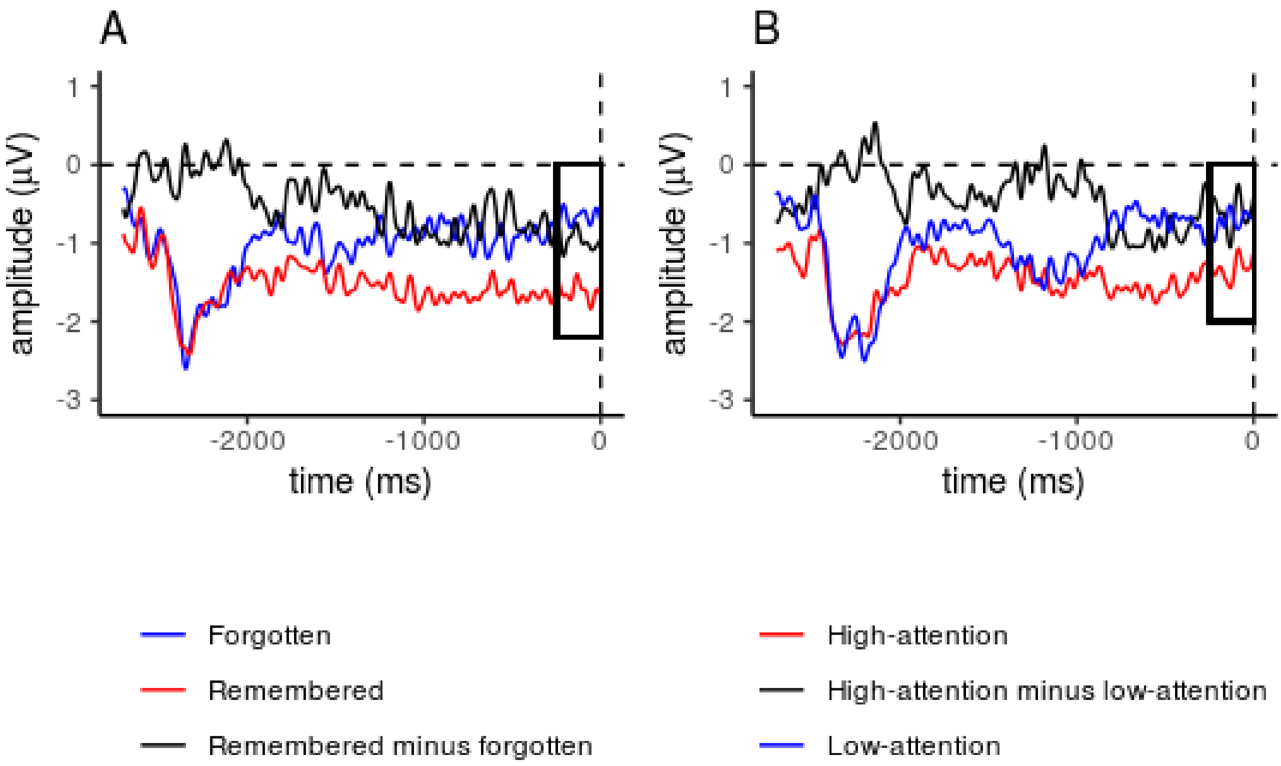

Figure 2.6 Grand-averaged ERP waveforms of the prestimulus interval in the encoding task (A) and attention task (B) at the averaged electrodes 18 and 22 corresponding to Fp1 of the 10-20 system. Timepoint 0ms denotes the onset of the cue. The box marks the -250ms to 0ms time-window selected for analyses.

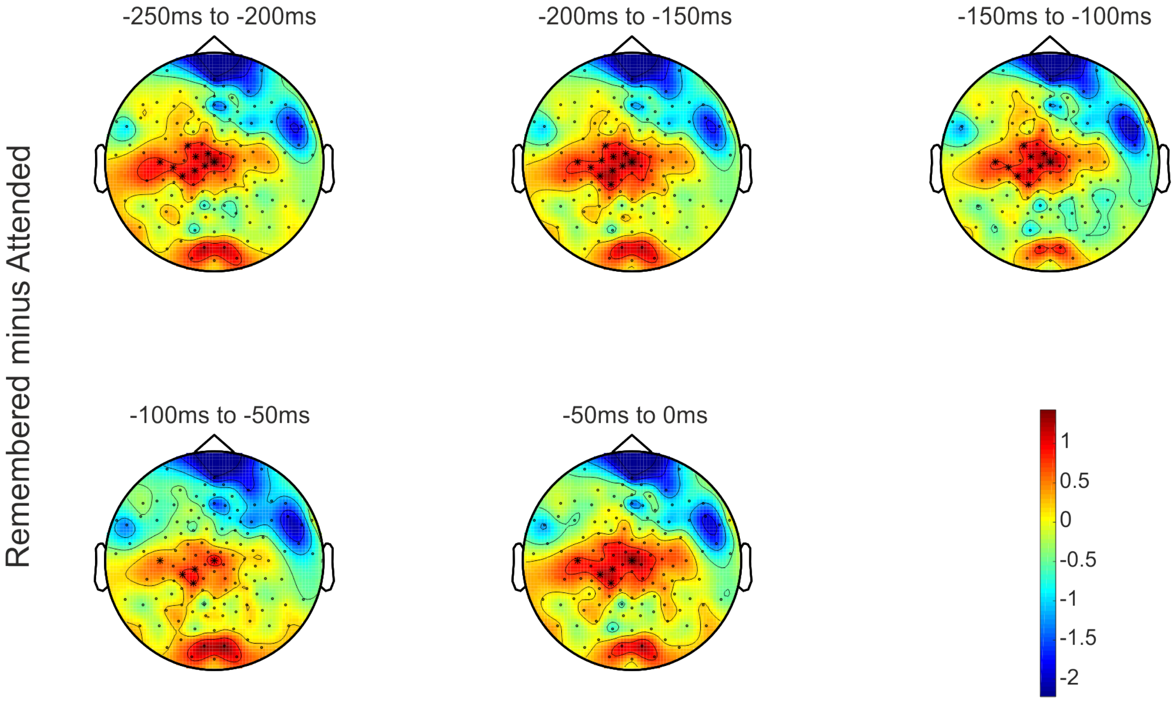

Figure 2.7 Significant cluster permutation results of the contrast between *remembered* and *high-attention* conditions. Results are plotted for the -250ms to 0ms time-window at steps of 50ms. The significant positive cluster is marked in bold.

2.3 Discussion

The aim of the present study was to replicate the psSME first reported by Otten et al. (2006) using a conservative approach and with high statistical power. Furthermore, I aimed at assessing whether such effect reflects semantic encoding or whether it reflects the influence of attentional processes over memory encoding. The experiment consisted of three tasks in the following order: an encoding task, an attention task and a surprise recognition task. In the encoding task, participants had to judge whether words belonged to an animate or inanimate object. In the attention task participants saw strings of letters and had to either give a response at each trial or only when the string was longer than five letters. Finally, in the surprise recognition task participants were presented with the words of the encoding task mixed with new words and had to judge whether they had seen the word in the encoding task and how confident were with their judgement. EEG data were collected throughout the encoding and attention task and ERPs were analysed during the prestimulus phase were analysed. Epochs from the encoding task were backsorted according to whether words were later remembered or forgotten in the recognition task. The conditions in the attention task were established a-priori.

2.3.1 Replication of the psSME

The first aim of the study was to replicate the classical psSME. We observed the amplitude preceding later remembered words to be more negative than later forgotten trials. The effect was congruent with that reported in Otten et al. (2006) and was statistically significant. Furthermore, the topography of the effect (first row - third column of fig 2.5) presents a similar phase reversal reported in Otten et al. (2006) (figure 2.1). One difference was that the positivity in our study peaked over central-left electrodes as compared to parietal-left electrodes in Otten et al. (2006). While these results suggest that I have replicated the classical psSME (see figure 2.8), conclusion should be drawn with caution. It could be argued that analyses were run on the same electrode analysed in the original paper and that the actual effect detected by our system might have shifted topography (fig. 2.5). However, cluster-based permutation exploratory analysis did not detect any difference between later remembered and later forgotten words in the last 250ms prestimulus time-window. Furthermore, in the original paper, the 58-channels EasyCap was used while in the present study the 129-channels HydroCell Geodesic Sensor Net was used for recordings. The different recording systems might have contributed to small shifts in topography.

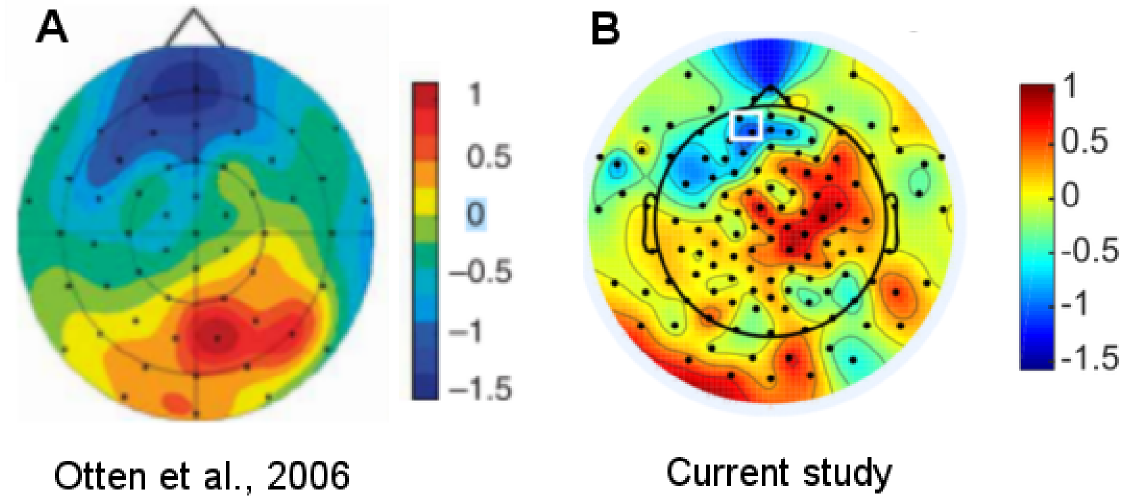

Figure 2.8 Side by side comparison on the psSME obtained by Otten et al. (2006) (A) and the psSME obtained in the current study (B).

2.3.2 Prestimulus attentional processes

The second aim of the study was to assess whether the psSME reflects attentional mechanisms rather than semantic processes. The attention task is a novel task that was developed specifically to engage anticipatory attentional processes with written stimuli while not engaging semantic processing. If the psSME was determined by attention I expected the prestimulus ERPs of *remembered* and *high-attention* and of *forgotten* and *low-attention* not to differ between the two tasks. Because the attention task is a novel task, in order to test our hypothesis regarding the psSME I first had to assess whether the prestimulus ERPs discriminated between high-attention and low-attention trials. This suggests that there was no difference between the two conditions. Therefore, I cannot claim that the attentional task has been able to distinguish between high and low attentional states.

The statistically negative outcome of the attention task could be ascribed to several factors. First, the attentional effect is small and the variability of the data high and therefore I was not able to detect the effect. This possibility is suggested by the large confidence intervals (fig. 2.4). Second, the task simply was not able to elicit variations in anticipatory attentional processes and therefore the lack of effect is a consequence of inefficient task design. Third, the effect of variations in attention allocation due to experimental manipulation was small, hence spontaneous fluctuations in attention throughout the task confounded the effect. Because the task investigates anticipatory prestimulus effects, the behavioural performance at each specific trial had little influence on trials inclusion. In other words, the interest was on the allocation of attentional resources regardless of whether the participant correctly identified a target. Therefore, the *d'* had the function of identifying whether participants performed the task as requested, taking into account the entirety of the experimental trials. If a participant showed to have complied with task instructions, it was assumed that anticipatory allocation of attentional resources was employed regardless of whether the subsequent stimulus was a target or a non-target and whether the judgement on the length of the stimulus was correct. This approach was adopted in order to maximize the number of available epochs for analysis and to obtain a similar number of trials in the two conditions. Indeed, analysing only correctly identified trials would have greatly reduced the number of available epochs in the *high-attention* condition. The drawback of such methodology is that there was little control over spontaneous fluctuations in sustained attention.

2.3.3 The psSME and attentional processes

In order to assess whether the psSME is influenced by attentional processess, the *remembered* condition was compared to the *high-attention* condition and the *forgotten* condition was compared to the *low-attention* condition. The attention task did not produce evidence for the modulation of anticipatory attentional processes in the two conditions. Hence, it is not possible to draw any conclusion on the nature of the psSME as attentive. For a purely anecdotal discussion of the data, we can observe in figure 2.4 and figure 2.6 that the direction of the psSME and the attention effect are similar. However, the big variability in the data does not allow to detect an effect in the behavioural task. Similarly, observing the topographies in figure 2.5 a negativity seems to appear in a similar location of the psSME. However, as reported in subsection 2.3.2, the voltage over most of the scalp topography of the attention effect approaches 0.

If I detected an attention effect and found no difference between the two tasks, I could have argued that the psSME was modulated by anticipatory attentional processes independently of semantic encoding. Indeed, Otten et al. (2006) suggested that the left-frontal psSME effect may be compatible with WM control over verbal material, such as phonological rehearsal and semantic maintenance (Ruchkin et al., 2003). However, the attention task simply required to judge the number of letters forming strings with no semantic meaning. Therefore, the recruitment of resources involving phonological or semantic processing was not necessary to perform the task.Nevertheless, the absence of a significant effect in the attention task does not allow us to interpret the observation that the data from the contrasts *remembered vs high-attention* and *forgotten vs low-attention* are drawn from the same distributions as evidence of similar processes modulating the psSME and the attention effect. Hence, the interpretation of the psSME as prefrontal negativity as reflecting the recruitment of a set of cognitive resources for semantically oriented encoding cannot be discarded (Otten et al., 2006; Pashler et al., 2001; Ruchkin et al., 2003).

Finally, cluster-permutation based analysis revealed a significant difference between *remembered* and *high-attention* trials over central-left electrodes. Because I did not a-priori expect a difference between these two conditions and because cluster-permutation analysis was run as exploratory, interpretation of these results are at the moment speculative. As I have just discussed, the encoding task required processing meaningful words while the attention task did not require any verbal processing. Hence, the difference between the two conditions may be determined by modulation of components that have been linked to the processing of semantic features for verbal material (Evans and Federmeier, 2007; Neville et al., 1986; Olichney et al., 2002a,b; Ruchkin et al., 2003).

2.3.4 Limitations and directions for future research

Carrying out the present study adopting a conservative approach has proved to be challenging. The major difficulty has been retaining participants and trials for statistical analysis. While 60 participants were tested, only 39 (two thirds of the sample) could be retained drastically reducing statistical power. Furthermore, as reported in subsection 2.2.5, only a handful of trials could be kept for analysis in each condition. That is problematic especially if dealing with potentially small effect sizes that can easily be overshadowed by variability within the data and that require high statistical power. We can identify two main features of the experiment that are responsible for this outcome. First, is the intrinsic feature of the encoding task for which trials are backsorted into conditions according to behavioural performance. Second, epochs were extremely long (3,200ms) and participants struggled in refraining themselves from blinking, causing a large number of trials to be rejected. The length of the epochs was the same as in Otten et al. (2006) for the sake of replication. However, in the original paper eye-blinks were corrected with regression-based methods. Other methods for eye-blinks correction such as ICA, PCA and toolboxes for automatised detection of artifactual components are available. However, I took the methodological decision of not manipulating the data beyond that strictly necessary for EEG preprocessing. In the future, the data could be reprocessed using an algorithm for eye-blink correction.

Another limitation of the study is a lack of control over spontaneous fluctuations of sustained attention. The attention task could be re-designed so that sustained attention can be monitored with behavioural data. For example, instead of asking participants to give a response only on target stimuli, the task could be designed so that a judgement on the current stimulus is required at every trial belonging to the *high-attention* condition.

Finally, future work should integrate TF analysis of the data.

2.4 Conclusions

In summary, the aim of the experiment was to replicate the psSME first reported by Otten et al. (2006) and to assess if such effect reflects allocation of attentional resources during memory encoding. While frequentist analysis replicated the psSME, the evidence obtained by bayesian analysis suggest that the present results are not conclusive. Furthermore, I could not find an attentional effect in the attention task and therefore no conclusion can be drawn from a comparison between the two tasks. It is possible that the attentional effect has been overshadowed by the variability within the data as a result of methodological constraints and the choice of a rigorous approach.

2.5 Declaration

The experiment reported in the present chapter constitutes original work. Giulia Cristoforetti contributed to data collection and Dr Lincoln Colling informed on analyses.

2.6 Appendix

ABDOMEN	animate	CAGE	inanimate	DOCK	inanimate	GRAVE	inanimate
ABORIGINE	animate	CAKE	inanimate	DOCUMENT	inanimate	GRAVY	inanimate
ACROBAT	animate	CALF	animate	DOLL	inanimate	GREASE	inanimate
ACTRESS	animate	CALORIE	inanimate	DOLPHIN	animate	GRENADE	inanimate
AERIAL	inanimate	CAMEL	animate	DOME	inanimate	GUITAR	inanimate
AEROSOL	inanimate	CAMERA	inanimate	DONKEY	animate	GUTTER	inanimate
AGENDA	inanimate	CANCER	animate	DOVE	animate	GYPSY	animate
AGNOSTIC	animate	CANDLE	inanimate	DRILL	inanimate	HADDOCK	animate
ALARM	inanimate	CANNON	inanimate	DRUM	inanimate	HAMMER	inanimate
ALCOHOL	inanimate	CANVAS	inanimate	DUCK	animate	HARDWARE	inanimate
AMULET	inanimate	CANYON	inanimate	DUNE	inanimate	HATCH	inanimate
ANCHOR	inanimate	CAPE	inanimate	DUNGEON	inanimate	HAWK	animate
ANKLE	animate	CAPILLARY	animate	DWARF	animate	HAZELNUT	animate
ANTIQUE	inanimate	CARDINAL	animate	EAGLE	animate	HEART	animate
ANVIL	inanimate	CARGO	inanimate	EARL	animate	HEDGE	animate
APPLE	inanimate	CARPET	inanimate	EASEL	inanimate	HELMET	inanimate
APRON	inanimate	CARROT	animate	ELEPHANT	animate	HERD	inanimate
ARENA	inanimate	CARTON	inanimate	ELLIPSE	inanimate	HERON	animate
ARTERY	animate	CASINO	inanimate	EMBASSY	inanimate	HINGE	inanimate
ARTIFACT	inanimate	CASTLE	inanimate	EMBRYO	animate	HOLLOW	inanimate
ASHTRAY	inanimate	CAVE	inanimate	EMERALD	inanimate	HOOF	animate
ASSASSIN	animate	CAVERN	inanimate	EMPEROR	animate	HOOP	inanimate
ASTERISK	inanimate	CELLAR	inanimate	ENCLAVE	inanimate	HORMONE	animate
ATHLETE	animate	CEMENT	inanimate	ENVELOPE	inanimate	HOSPICE	inanimate
ATLAS	inanimate	CHALK	inanimate	ENVOY	animate	HOSTAGE	animate
ATTIC	inanimate	CHAPEL	inanimate	ENZYME	animate	HUNTER	animate
AUNT	animate	CHARITY	inanimate	EQUATOR	inanimate	IGNITION	inanimate
AVIATOR	animate	CHEF	animate	ERASER	inanimate	INSULIN	animate
AXLE	inanimate	CHERRY	animate	ESSAY	inanimate	INTESTINE	animate
BACTERIA	animate	CHICK	animate	EXPORT	inanimate	INTRUDER	animate
BADGE	inanimate	CHILL	inanimate	EYEBALL	animate	IVORY	animate
BALE	inanimate	CHIMNEY	inanimate	FALCON	animate	JAIL	inanimate
BALLOON	inanimate	CHISEL	inanimate	FEAST	inanimate	JANITOR	animate
BANANA	inanimate	CIRCUIT	inanimate	FERRY	inanimate	JAWBONE	animate
BANDAGE	inanimate	CLAM	animate	FIGURINE	inanimate	JEEP	inanimate
BANGLE	inanimate	CLARINET	inanimate	FILTER	inanimate	JEWEL	inanimate
BANJO	inanimate	COBBLER	animate	FIREMAN	animate	JUGULAR	animate
BARRIER	inanimate	COCKTAIL	inanimate	FISH	animate	JUNGLE	animate
BASKET	inanimate	COIL	inanimate	FLASK	inanimate	JUROR	animate
BAUBLE	inanimate	COIN	inanimate	FLEA	animate	KENNEL	inanimate
BEAD	inanimate	COLLAR	inanimate	FLESH	animate	KETTLE	inanimate
BEAKER	inanimate	COLT	animate	FLOOD	inanimate	KEYBOARD	inanimate
BEAR	animate	COMPUTER	inanimate	FLUTE	inanimate	KIDNEY	animate
BEDROOM	inanimate	COMRADE	animate	FOAL	animate	KIPPER	animate
BEETLE	animate	CONCRETE	inanimate	FOLDER	inanimate	KITTEN	animate
BENCH	inanimate	CONSTABLE	animate	FOREARM	animate	KNEE	animate
BICEPS	animate	CONVICT	animate	FORK	inanimate	KNIGHT	animate
BIKINI	inanimate	COPPER	inanimate	FREEZER	inanimate	KNUCKLE	animate
BISCUIT	inanimate	CORD	inanimate	FROST	inanimate	LACE	inanimate
BISHOP	animate	CORK	animate	FUNGUS	animate	LADLE	inanimate
BLADDER	animate	CORN	animate	FURNACE	inanimate	LAGOON	inanimate
BLADE	inanimate	COSMETIC	inanimate	GALLON	inanimate	LAMB	animate
BLAZER	inanimate	COSTUME	inanimate	GARAGE	inanimate	LANCE	inanimate
BLISTER	animate	COUPON	inanimate	GARMENT	inanimate	LANTERN	inanimate
BLIZZARD	inanimate	COVE	inanimate	GAZELLE	animate	LARDER	inanimate
BOLT	inanimate	COWBOY	animate	GEAR	inanimate	LARYNX	animate
BOOTH	inanimate	COYOTE	animate	GENE	animate	LATCH	inanimate
BRAKE	inanimate	CRAB	animate	GERM	animate	LATTICE	inanimate
BRICK	inanimate	CRADLE	inanimate	GEYSER	inanimate	LEAF	animate
BROCHURE	inanimate	CRATE	inanimate	GILLS	animate	LEAFLET	inanimate
BRONZE	inanimate	CRIMINAL	animate	GIRAFFE	animate	LEASE	inanimate
BROTHEL	inanimate	CROW	animate	GLACIER	inanimate	LEDGER	inanimate
BUBBLE	inanimate	CUBE	inanimate	GLAND	animate	LEMON	animate
BUCKET	inanimate	CUCUMBER	animate	GLIDER	inanimate	LEOPARD	animate
BULL	animate	CYST	animate	GLOBE	inanimate	LIGAMENT	animate
BULLET	inanimate	DAFFODIL	animate	GLOVE	inanimate	LIMB	animate
BUOY	inanimate	DAISY	animate	GLUE	inanimate	LINEN	inanimate
BURGLAR	animate	DEER	animate	GOAT	animate	LION	animate
BUSH	animate	DENTIST	animate	GOOSE	animate	LIZARD	animate
BUTTON	inanimate	DENTURE	inanimate	GOWN	inanimate	LOBSTER	animate
CABBAGE	animate	DETERGENT	inanimate	GRANDSON	animate	LOCK	inanimate
CABIN	inanimate	DIAGRAM	inanimate	GRANITE	inanimate	LOOP	inanimate
CABINET	inanimate	DIGITAL	inanimate	GRANULE	inanimate	LUGGAGE	inanimate
CABLE	inanimate	DINGO	animate	GRAPE	animate	LUNAR	inanimate
CAFE	inanimate	DITCH	inanimate	GRAPH	inanimate	LYNX	animate

Table 2.3 Words from A to L used in the original experiment (Otten et al., 2006) with the respective animacy judgement. Courtesy of Dr L.J. Otten.

MACKEREL	animate	PECTORAL	animate	RUBBER	inanimate	SWORD	inanimate
MAGGOT	animate	PELICAN	animate	RUST	inanimate	SYRINGE	inanimate
MAGICIAN	animate	PELVIS	animate	SACK	inanimate	TABLET	inanimate
MAGNET	inanimate	PENGUIN	animate	SAILOR	animate	TATTOO	inanimate
MAMMAL	animate	PETAL	animate	SALMON	animate	TAVERN	inanimate
MANGO	inanimate	PHEASANT	animate	SAPLING	animate	TELEGRAM	inanimate
MANSION	inanimate	PIANO	inanimate	SARDINE	animate	TENDON	animate
MARBLE	inanimate	PICKLE	animate	SATCHEL	inanimate	TERRIER	animate
MARE	animate	PIER	inanimate	SATIN	inanimate	THIGH	animate
MASK	inanimate	PIGEON	animate	SAUCER	inanimate	THIMBLE	inanimate
MAST	inanimate	PILLAR	inanimate	SCALLOP	animate	THROAT	animate
MATRON	animate	PIPE	inanimate	SCALP	animate	THRONE	inanimate
MAZE	inanimate	PISTON	inanimate	SCARF	inanimate	TIGER	animate
MELON	animate	PIXIE	inanimate	SEDIMENT	inanimate	TOAD	animate
METEOR	inanimate	PLANK	inanimate	SEED	animate	TOMATO	animate
MINERAL	inanimate	PLAQUE	inanimate	SENSOR	inanimate	TOMB	inanimate
MINK	animate	PLIERS	inanimate	SHARK	animate	TONGUE	animate
MIST	inanimate	PLUG	inanimate	SHAWL	inanimate	TONSIL	animate
MOLE	animate	PLUM	animate	SHED	inanimate	TORSO	animate
MOLECULE	inanimate	PLUMBER	animate	SHEEP	animate	TOURIST	animate
MONK	animate	PODIUM	inanimate	SHERIFF	animate	TOWEL	inanimate
MONKEY	animate	POKER	inanimate	SHRAPNEL	inanimate	TOWER	inanimate
MOOSE	animate	POLLEN	animate	SHRIMP	animate	TRICEPS	animate
MOSQUE	inanimate	PONY	animate	SILICON	inanimate	TROTTER	animate
MOSQUITO	animate	POODLE	animate	SILK	animate	TROUT	animate
MOTH	animate	POPE	animate	SINEW	animate	TULIP	animate
MOUSE	animate	POPPY	animate	SINUS	animate	TUMOUR	animate
MOUSTACHE	animate	PORK	animate	SKEWER	inanimate	TUNA	animate
MULE	animate	POSTER	inanimate	SKULL	animate	TUNIC	inanimate
MUSHROOM	animate	POTATO	animate	SKUNK	animate	TURBINE	inanimate
NANNY	animate	POULTRY	animate	SKYLARK	animate	TURNIP	animate
NATIVE	animate	PRAM	inanimate	SLEDGE	inanimate	TURTLE	animate
NECK	animate	PRAWN	animate	SLEEVE	inanimate	TUSK	animate
NEEDLE	inanimate	PREACHER	animate	SLIPPER	inanimate	UDDER	animate
NEURON	animate	PRIMATE	animate	SLUG	animate	ULCER	animate
NITROGEN	inanimate	PRINCE	animate	SMOG	inanimate	UTERUS	animate
NOSTRIL	animate	PULLEY	inanimate	SNAIL	animate	VEIN	animate
NUCLEUS	animate	PUMPKIN	animate	SNORKEL	inanimate	VERMIN	animate
NURSE	animate	PUPPY	animate	SNOUT	animate	VICAR	animate
NYLON	inanimate	PURSE	inanimate	SOAP	inanimate	VINE	animate
OLIVE	animate	PUZZLE	inanimate	SOCKET	inanimate	VIOLIN	inanimate
ONION	animate	PYTHON	animate	SOLICITOR	animate	VIRUS	animate
ORCHID	animate	RABBI	animate	SPACE	inanimate	VODKA	inanimate
OSTRICH	animate	RABBIT	animate	SPADE	animate	VULTURE	animate
OTTER	animate	RACKET	inanimate	SPANIEL	animate	WAITER	animate
OXEN	animate	RADISH	animate	SPATULA	inanimate	WALNUT	animate
OYSTER	animate	RAFT	inanimate	SPEAR	animate	WALRUS	animate
OZONE	inanimate	RASPBERRY	animate	SPICE	animate	WART	animate
PACKET	inanimate	RAVEN	animate	SPIDER	animate	WASP	animate
PAINT	inanimate	RAZOR	inanimate	SPINACH	animate	WEASEL	animate
PAMPHLET	inanimate	REACTOR	inanimate	SPINDLE	inanimate	WEDGE	inanimate
PANDA	animate	RECEIPT	inanimate	SPRAY	inanimate	WHALE	animate
PANSY	animate	RECIPE	inanimate	SPROUT	animate	WHIP	inanimate
PANTHER	animate	RECTANGLE	inanimate	STAIRWAY	inanimate	WICKET	inanimate
PARADE	inanimate	REPTILE	animate	STALLION	animate	WIDOW	animate
PARASITE	animate	RETINA	animate	STAPLE	inanimate	WOLF	animate
PARCEL	inanimate	RHUBARB	animate	STATUE	inanimate	WOMB	animate
PARROT	animate	ROBE	inanimate	STEEPLE	inanimate	WORM	animate
PASSPORT	inanimate	ROBIN	animate	STEROID	animate	WRIST	animate
PATIO	inanimate	ROBOT	inanimate	STOOL	inanimate	ZEBRA	animate
PEACH	animate	RODENT	animate	STORK	animate	ZINC	inanimate
PEACOCK	animate	ROOSTER	animate	SUITCASE	inanimate		
PEAR	animate	ROOT	animate	SURGEON	animate		
PEARL	animate	ROSE	animate	SWAN	animate		

Table 2.4 Words from M to Z used in the original experiment (Otten et al., 2006) with the respective animacy judgement. Courtesy of Dr L.J. Otten.

ADOLESCENT	animate	CANDLE	inanimate	DAMP	inanimate	FOGG	inanimate
ADULT	animate	CANDY	inanimate	DANCER	animate	FOLKS	animate
AIRPORT	inanimate	CAKE	inanimate	DAUGHTERS	animate	FORK	inanimate
ALARM	inanimate	CANVAS	inanimate	DAWN	inanimate	FRINGE	inanimate
ALIEN	animate	CARBON	inanimate	DAYTIME	inanimate	FLUTE	inanimate
ALUMINUM	inanimate	CARD	inanimate	DEALER	animate	FLASK	inanimate
AMBASSADOR	animate	CATS	animate	DEER	animate	FUEL	inanimate
ANACONDA	animate	CELLAR	inanimate	DEMOCRAT	animate	GALLERY	inanimate
ANCHOR	inanimate	CARPET	inanimate	DENTIST	animate	GLOVE	inanimate
ANGELS	animate	CHAIRMEN	animate	DESERT	inanimate	GATES	inanimate
ARCH	inanimate	CHAMPIONS	animate	DESIGNER	animate	GEAR	inanimate
ARCHITECTS	animate	CHANCELLOR	animate	DETERGENT	inanimate	GOOSE	animate
ARROW	inanimate	CHANNEL	inanimate	DEVIL	animate	GENTLEMAN	animate
AUNT	animate	CHEETAH	animate	DICTATOR	animate	GRANDSON	animate
AUTHORS	animate	CHEF	animate	DIMENSION	inanimate	GYPSY	animate
BABIES	animate	CHRISTIANS	animate	DISK	animate	GIFT	inanimate
BEETLES	animate	CIGARETTE	inanimate	DOCTORS	animate	GOAT	animate
BANKERS	animate	CIRCUIT	inanimate	DOCUMENT	inanimate	GOVERNORS	animate
BARBECUE	inanimate	CITIZEN	animate	DOLPHINS	animate	GOWN	inanimate
BARBER	animate	CIVILIAN	animate	DOME	inanimate	GRADUATES	animate
BASS	inanimate	CLASSMATE	animate	DOORWAY	inanimate	GRAIN	inanimate
BATHROOM	inanimate	CLEANER	animate	DOSE	inanimate	GRAMDMA	animate
BUTTON	inanimate	CLERK	animate	DRAGONS	animate	GRAMS	inanimate
BEARS	animate	CLIENT	animate	DRIVEWAY	inanimate	GRAVE	inanimate
BEAVER	animate	CLOSET	inanimate	DUKE	animate	GUARANTEE	inanimate
BEER	inanimate	CLOTHING	inanimate	DUNES	inanimate	GAZELLE	animate
BEES	animate	CLOUD	inanimate	ECHO	inanimate	GUARDS	animate
BELL	inanimate	CLUE	inanimate	EMERALD	inanimate	GUITAR	inanimate
BELT	inanimate	COCKPIT	inanimate	ELECTRON	inanimate	GULF	inanimate
BIRD	animate	CRADLE	inanimate	ELEPHANT	animate	GYMNASTS	animate
BLAZER	inanimate	COIL	inanimate	EMPEROR	animate	HATS	inanimate
BLANKET	inanimate	COLLAGE	inanimate	EMPLOYER	animate	HEROES	animate
BOOTS	inanimate	COLLEAGUE	animate	ENEMIES	animate	HISTORIAN	animate
BOSS	inanimate	COMB	inanimate	ENGINEERS	animate	HONEY	inanimate
BOTTLES	inanimate	COMMANDER	animate	ERASER	inanimate	HOSTESS	animate
BOWL	inanimate	COMMUTER	animate	ENVELOPE	inanimate	HUMANS	animate
BOXES	inanimate	COMPANION	animate	EROSION	inanimate	HUNTER	animate
BRANCH	inanimate	COMPOSER	animate	FABRIC	inanimate	HUSBANDS	animate
BRASS	inanimate	CONSUMERS	animate	FALCON	animate	INFANT	animate
BREEZE	inanimate	CONTROLLER	animate	FARMER	animate	INSECT	animate
BRIDE	animate	CHALK	inanimate	FILTER	inanimate	INSPECTOR	animate
BUBBLES	inanimate	COUSINS	animate	FATHERS	animate	INSTRUCTOR	animate
BUFFALO	animate	COWBOY	animate	FEATHER	inanimate	INTERVAL	inanimate
BUFFER	inanimate	CREATURE	animate	FEES	inanimate	INVENTOR	animate
BUGS	animate	CROWN	inanimate	FELLOWS	animate	ISLANDS	inanimate
BUILDER	animate	CUPS	inanimate	FENCE	inanimate	IVORY	inanimate
BULL	animate	CURE	inanimate	FESTIVAL	inanimate	JAGUAR	animate
BUTCHER	animate	CURRICULUM	inanimate	FIGHTERS	animate	JEANS	inanimate
BUTLER	animate	CURTAIN	inanimate	FILES	inanimate	JEEP	inanimate
BUTTER	inanimate	CUSTOMER	animate	FISH	animate	JUICE	inanimate
CAFE	inanimate	CYCLIST	animate	FLAME	inanimate	JUNIORS	animate
CALENDAR	inanimate	DAME	animate	FLIGHTS	inanimate	JUNK	inanimate

Table 2.5 Words from A to J with the respective animacy judgement used in the present experiment.

KEYBOARD	inanimate	NITROGEN	inanimate	PRISONERS	animate	SPRAY	inanimate
KEYS	inanimate	NOVELIST	animate	PRIZE	inanimate	STATUE	inanimate
KETTLE	inanimate	NUNS	animate	PRODUCER	animate	STORM	inanimate
KIDS	animate	NURSE	animate	PROPHET	animate	STOVE	inanimate
KILLER	animate	NUTRIENTS	inanimate	PUPILS	animate	STRAW	inanimate
KNIGHT	animate	OBSERVERS	animate	PUPPY	animate	STRING	inanimate
KNOT	inanimate	OBSTACLE	inanimate	PYTHON	animate	SUBMARINE	inanimate
LABEL	inanimate	OILS	inanimate	QUANTUM	inanimate	SOLICITOR	animate
LADIES	animate	ODORS	inanimate	QUEENS	animate	SUGAR	inanimate
LAGOON	inanimate	OVAL	inanimate	RABBI	animate	SULTAN	animate
LAMB	animate	OMELET	inanimate	RABBIT	animate	SUSPECT	animate
LAMP	inanimate	OVERCOAT	inanimate	RAILWAY	inanimate	TAPE	inanimate
LANDLORD	animate	OUTFIT	inanimate	RANCHER	animate	TAXI	inanimate
LANE	inanimate	OWNER	animate	REBELS	animate	TAXPAYER	animate
LAWYERS	animate	PACK	inanimate	RECTOR	animate	TEARS	inanimate
LAYER	inanimate	PAGES	inanimate	RELATIVES	animate	TESTAMENT	inanimate
LEAFLET	inanimate	PAINTER	animate	REPORTER	animate	THERAPIST	animate
LEVER	inanimate	PARROT	animate	RESIDENCE	inanimate	THIEF	animate
LECTURER	animate	PARENT	animate	ROOSTER	animate	TICKET	inanimate
LIEUTENANT	animate	PARLOR	inanimate	RIDER	animate	TIGER	animate
LOTION	inanimate	PLUMBER	animate	ROOKIE	animate	TATOO	inanimate
LION	animate	PASSENGER	animate	RAZOR	inanimate	TOAST	inanimate
LISTENERS	animate	PASTOR	animate	ROPE	inanimate	THRONE	inanimate
LIZARDS	animate	PATRIOT	animate	ROWS	inanimate	TOWEL	inanimate
LUNCH	inanimate	PAYROLL	inanimate	RUBBER	inanimate	TOOLS	inanimate
LOAF	inanimate	PEACOCK	animate	SAILORS	animate	TOURIST	animate
MADAME	animate	PRIMATE	animate	SAINT	animate	TRACT	inanimate
MAID	animate	PENCIL	inanimate	SALESMAN	animate	TRAINS	inanimate
MOTEL	inanimate	PERFORMERS	animate	SCENERY	inanimate	TRAVELER	animate
MARTYR	animate	PETITIONER	animate	SCHEME	inanimate	TUBE	inanimate
MOTH	animate	PHARMACY	inanimate	SCHOLAR	animate	TURKEY	animate
MEADOW	inanimate	PHYSICIAN	animate	SCIENTIST	animate	TURTLE	animate
MEAL	inanimate	PIANIST	animate	SEATS	inanimate	TROUT	animate
MEDICINE	inanimate	PIGEON	animate	SERGEANT	animate	VECTOR	inanimate
MERCHANT	animate	PILL	inanimate	SERVANTS	animate	VESSEL	inanimate
MILLS	inanimate	PIONEER	animate	SHADE	inanimate	VETERAN	animate
MINERAL	inanimate	PIRATES	animate	SHAPES	inanimate	VICAR	animate
MINISTERS	animate	PLANES	inanimate	SHEEP	animate	VICTIMS	animate
MIRROR	inanimate	PLASTER	inanimate	SHEETS	inanimate	VICTOR	animate
MIST	inanimate	PLASTIC	inanimate	SHERIFF	animate	VISITOR	animate
MAGICIAN	animate	PLAYERS	animate	SHIRT	inanimate	VOLUNTEER	animate
MONK	animate	POETS	animate	SHOWER	inanimate	VOTER	animate
MOTHERS	animate	POLE	inanimate	SILVER	inanimate	WHIP	inanimate
MOUNTAIN	inanimate	POLICEMEN	animate	SINGERS	animate	WARRIORS	animate
MOUSE	animate	PONY	animate	SKETCH	inanimate	WASTE	inanimate
MURDERER	animate	PORK	animate	SLAB	inanimate	WHISKEY	inanimate
MUSE	animate	PORTER	animate	SLEEVE	inanimate	WIDOW	animate
MUSEUM	inanimate	PARCEL	inanimate	SNAKES	animate	WAITER	animate
MUSICIAN	animate	POUND	inanimate	SOAP	inanimate	WEDGE	inanimate
MUSTARD	inanimate	POWDER	inanimate	SONS	animate	WORKER	animate
NYLON	inanimate	PREACHER	animate	SOUP	inanimate	YOUNGSTERS	animate
NARRATOR	animate	PREY	animate	SNAIL	animate	ZENITH	inanimate
NEEDLE	inanimate	PRINCE	animate	SPHERE	inanimate	ZONE	inanimate

Table 2.6 Words from K to Z with the respective animacy judgement used in the present experiment.

2.7 References

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Chapter 3

A resource model account of the effects of anxiety on visuospatial working memory

3.1 Introduction

3.1.1 The effects of anxiety on WM

Anxiety is an aversive emotional and motivational state that occurs in situations of anticipated threat. It is often associated with adverse effects on the performance of cognitive tasks (Eysenck et al., 2007; Eysenck and Calvo, 1992). Anxiety can impact WM which is considered to be a limited capacity system that temporarily retains and manipulate information necessary for many complex cognitive activities (Baddeley, 1992; Miller and A., 1956). The detrimental effects of anxiety on processing efficiency have been explained within Baddeley's working memory model (Baddeley, 1992). According to this model, WM is a limited capacity system formed of several components: a modality-free central executive (CE) involved in the processing of information and having self-regulatory functions; a phonological loop that holds verbal and acoustic information using a temporary store and an articulatory rehearsal system; a visuospatial sketchpad for the processing and transient storage of visual and spatial information; an episodic buffer that serves as temporary storage system which is capable of integrating information from a variety of sources. The main effects of anxiety were typically thought to be on the CE (Eysenck et al., 2007) as a result of attentional biases occurring in anxiogenic situations, such as attentional shift on self evaluative focus on physiological arousal, enhanced recognition of threat and attention narrowing on the sources of threat (Barlow, 2000).

Some studies have suggested that the detrimental effects of anxiety on verbal WM and VSWM are smaller than those on the CE or non-existent (Eysenck et al., 2007, 2005). On the other hand, studies using a spatial n-back task have shown that VSWM is impaired during experimentally induced anxiety (Clarke and Johnstone, 2013; Lavric et al., 2003; Li et al., 2006; Shackman et al., 2006). Impairments in VSWM tasks have also been observed in participants with anxiety disorders, although findings are not consistent. For example, obsessive compulsive disorder patients performed poorly in a spatial n-back task (Van Der Wee et al., 2003). However, in a change detection task (Vogel and Machizawa, 2004) where participants had to decide whether a set of coloured squares was the same of the previous set, high trait anxiety participants did not under-perform as compared to controls (Qi et al., 2014). Nevertheless, electroencephalography data suggested that high trait anxiety participants have reduced VSWM capacity (Qi et al., 2014).

A crucial aspect for the understanding of the effect of anxiety on VSWM, is the functional overlap between mechanisms of VSWM and spatial selective attention (Awh and Jonides, 2001). Firstly, top-down attentional control determines which stimuli will be stored in memory. Secondly, if more than one item is represented in WM, covert shifts of spatial attention could underlie the maintenance of information in VSWM as a rehearsal mechanism (Awh et al., 2006; Smyth and Scholey, 1994). Furthermore, neuroimaging studies have shown a neuroanatomical overlap between spatial attention and WM networks. Indeed prefrontal and parietal brain regions have been found to aid both spatial attention and WM (Lepsien et al., 2005; Mayer et al., 2007). It has been suggested that the mechanism through which anxiety impairs VSWM is via the elective depletion of limited resources. Research has indeed indicated that neuronal networks instantiating anxious arousal and the neuronal networks activated in various form of VSWM and spatial attention partially overlap in the right prefrontal cortex and in the right posterior parietal cortex (Adhikari et al., 2010; Dalton et al., 2005; Manoach et al., 2004). It is, therefore, possible that anxious arousal competes with ongoing cognitive operations as they share common neuronal networks.

It could be argued that the relationship between anxiety and WM may follow the opposite direction. It may be that the loading of WM reduces the resources available for emotion regulation. It has been proposed that cognitive ability contributes to the control of emotional responding (Schmeichel et al., 2008) such as the ability of modulating complex behavioural responses and the reappraisal of emotional stimuli (Ochsner and Gross, 2008). In the context of MA, some evidence points towards a causal effect of cognitive resources over anxious responding, while other authors suggest a reciprocal influence (Carey et al., 2016). However, in these cases emotion regulation is defined as complex behaviours and cognitive coping strategies. On the other hand, the present research question is framed in terms of basic properties of WM. In this context, the ACT provides a theoretical framework for the explanation of the relationship between WM and anxiety. Keeping in mind that it might provide a partial description of the phenomenon, such framework has been adopted as starting point for the work carried out in this chapter.

3.1.2 Models of VSWM

Typically, research on VSWM has used binary tasks, namely tasks whose answer is given on a binary fashion (e.g., correct vs incorrect). Those tasks are suitable for investigating VSWM as conceptualized by slot models. According to these models, WM is considered to be a limited capacity system able to store only a small number of items (Cowan, 2010; Miller and A., 1956). Specifically, VSWM is composed of a small number of slots and each slot can retain one item only, whose features are incorporated and bound all together. Those objects that have gained access into a memory slot will be remembered accurately, while competing objects that did not get into a memory slot will not be remembered at all (for a full review see Ma et al., 2014). Visual attention is the means through which competing objects gain or do not gain access to a slot (Cowan, 2010).

Recently, the slot model has been challenged by studies that used the delayed-estimation technique (Wilken and Ma, 2004). In such technique, participants have to recall features of a target stimulus. The features of the target stimulus and the possible responses vary on a continuous scale and it is therefore possible to assess how much the value of the recalled feature deviates from the value of the target. These studies have observed behavioural effects that are incompatible with the slot model, according to which items are early encoded in a binary fashion and with their features integrated and bound together. For example, the accuracy of recall has been shown to decline as the number of stimuli increases and errors in recalling have been shown to be distributed in the space of possible responses (Bays et al., 2009, 2011a; Bays and Husain, 2008; Zhang and Luck, 2008a). In another study, Bays et al. (2011b) showed that each visual feature of a target item presents its own Gaussian distribution of errors centred on the target value. Furthermore, in large arrays a subset of responses were clustered around feature values belonging to non-target objects present in the array. Bays et al. (2011a) also found that cued items had a recall advantage and such effect was observed even when the item had already been encoded. These effects have been explained by resource models of VSWM. According to resource models, limited resources are flexibly allocated across the set of the objects to be remembered.

The exact distribution of the statistical model that best explains VSWM precision of recall data is still debated. According to equal-resource models (Bays and Husain, 2008; Wilken and Ma, 2004) error variability increases with the number of items to be remembered because attentional resources are equally allocated across items. In this model, error distribution follows a Von Mises distribution with mean zero and the variability parameter κ reflecting error variability. According to the discrete-representation model (Zhang and Luck, 2008a), WM is instead composed of discrete memory slots. This model can be included under the umbrella of the resource models. That is because it states that discrete slots are shared between items. For small set-sizes, the resources available for each slot combine. Resulting in high-resolution memory representations for the items. On the other hand, for big set-sizes, each slot supervises the representation of one single item and items that do not fall within any slot will be forgotten. Similarly to equal-resource models, errors follow a von Mises distribution with variability expressed by the parameter κ. However, the distribution also includes a uniform parameter u for items that have not been stored in any slot. Hence, error recollection for items that have not been stored in any slot stems from purely random guesses. Bays et al. (2009) however, proposed that errors in recollecting the features of a target item might also be influenced by the interference of other non-target items present in the memory array. According to the probabilistic mixture model, the response distribution is formed by three components: the distribution of responses with mean zero and with variability κ_t, the uniform (u) distribution of random guesses, and the distribution of responses centred at the value of one of the non-target items with variability κ_{nt}.

3.1.3 Anxiety in the framework of resource models of VSWM

The distribution of errors in the recollection of a stimulus is determined by noise. Such noise can affect the recalling process at different stages, namely early sensory processing, retention, and retrieval (Ma et al., 2014). So far, sources of noise have been identified as physical stimulus factors (Ma et al., 2014), set size (Bays and Husain, 2008), and time available for encoding or decoding (Bays et al., 2011a; Pertzov et al., 2013). Interest in such sources of noise has been driven by the assumption that the allocation of limited resources depends on two factors: the interference generated by competing items and goal directed attentional mechanisms. However, no investigation has yet been carried out looking at the effects of external and item-independent noise. Task-irrelevant anxiety may indeed act as an external source of noise. The attentional shift and biases (Barlow, 2000) may interfere with top-down mechanisms involved in the encoding and decoding of visuospatial properties of the items to be remembered. For example, anxiety induced by the administration of electric shocks has been shown to disrupt the activity associated with the evaluation of task-relevant information, biasing attention and resource allocation (Rossi and Pourtois, 2015; Shackman et al., 2011).

VSWM has been found to be affected by anxious states (Lavric et al., 2003; Li et al., 2006; Shackman et al., 2006). One possible explanation is that anxiety has a detrimental effect on performance of VSWM tasks because it interferes with resource allocation and biases attention away from task relevant information (Rossi and Pourtois, 2015; Shackman et al., 2011). Importantly, flexibility in resource allocation in combination with noise is thought to explain the error distribution in resource models of WM (Ma et al., 2014).

3.1.4 Rationale of the study

In this study I aimed at investigating the effects of anxiety on VSWM in the framework of the resource models of VSWM. Indeed, anxiety is characterized by attention biases towards threat-relevant stimuli (e.g., Pflugshaupt et al., 2005) and by shifts towards self evaluative focus (Barlow, 2000), which may decrease the attentional resources available for performing tasks. I assessed VSWM by means of accuracy on a continuous scale rather than in a binary fashion. To this aim, I used a modified version of the task developed by Bays et al. (2011b). The delayed-estimation task was adopted to assess whether anxiety impacted on the ability of dealing with the noise intrinsic to memory representations. I manipulated the level of negative arousal varying the probability of receiving a shock at the end of each trial. This methodology was informed by the NPU-threat test protocol (Schmitz and Grillon, 2012). Behavioural responses were analysed by comparing the estimates of the discrete-representation model (Zhang and Luck, 2008a) for both colour and angle features. The two features were measured to assess the precision of recall of both visual and spatial information in VSWM. Because Bays et al. (2011b) report that misreporting occur independently for features of an item, we believed that assessing both would not result in trade-offs between the two features that would affect the data.

A no-memory task in which there was no retention interval was also administered. Anxiety is thought to drive attention away from task relevant stimuli. Hence, a decrease in performance might have been modulated by the effect of anxiety over aspects of performance not directly related to memory. For example, participants might have been less accurate simply because they wanted to quickly respond to the trials and get over the experimental block. If that was the case, also performance to a task that does not require the retention of items in WM would be affected. The no-memory task allowed to test whether the decrease in performance was disengaged from WM. If a decrease in performance due to anxiety was present in data from the orientation task and not in data from the no-memory task, I could conclude that VSWM processes are indeed affected by anxiety.

3.2 Materials and methods

3.2.1 Participants

Seventeen participants (9 females, 8 males) took part to the study after giving informed consent. All subjects had normal or corrected-to-normal vision, no colour blindness, no history of psychiatric conditions, and no cardiac pacemaker. Participants were paid £50 for their participation upon completion of both sessions of the experiment.

The study was approved by the University of Cambridge Psychology Research Ethics Committee.

3.2.2 Task and stimuli

Orientation task

Each trial began with a 1000ms presentation of a cue that predicted the probability of receiving an electric shock at the end of the trial. The cue was followed by 300ms blank interval. Next, a memory array of three coloured oriented arrows was presented for 2000ms followed by a pattern mask for 100ms and then a blank retention interval (900ms). The pattern mask was included to ensure iconic memory did not contribute to performance. A single vertical test arrow (white) was then presented at one randomly chosen location from the preceding memory array. Subjects were instructed to adjust the angle and colour of the test arrow to match the features of the probed arrow of the memory array (Fig. 3.1A).

The arrows of the memory set were randomly distributed at eccentricities with x and y coordinates in the range -423 to 422 pixels, the centre of the screen being (0,0). Angle and colour were independently chosen at random from two circular parameter spaces. The angle parameter space corresponded to the range of angles –180°to +180°(i.e. the full range of possible arrow orientations). For colour, we used the guidelines in Zhang and Luck (2008b). The parameter space was defined 180 colour values distributed in a L*a*b* colour space. The parameters of the colour space were defined as L*$\approx$ 54, a*$\approx$22.5+55 $\times$ cos(θ), and b*$\approx$ 11+46$\times$ sin(θ), where θ ranged from 2°to 360°in 2°steps. This circle was centred in the colour space at (L = 70, a = 20, b = 38) with a radius of 60. Its centre was chosen to maximize its radius and therefore the discriminability of the colours. All colours had equal luminance and varied mainly in hue and slightly in saturation.

The features were adjusted using two input dials (X-box Wireless Controller, Microsoft, USA. Fig. 3.1C). The right one was controlled with the right hand and the left one with the left hand. Turning one dial caused the probe to rotate through the range of possible angles; turning the other dial caused the probe's colour to cycle through the space of possible values.

Subjects could adjust the two dials in any order or simultaneously, and indicated adjustment was complete by pressing the green "A" button.

There were four experimental blocks of 75 trials each. On 12 randomly chosen trials per block, the mask onset was timed with the onset of a 102dB, 50ms long white noise presented binaurally via headphones. Immediately after the white noise offset, a 100ms electric shock was or was not administered according to the experimental condition. The rationale for presenting the white noise before the administration of the shock was to elicit the startle reflex while anxiety was induced by the anticipation of threat. In other words, eliciting the startle reflex during such anticipation would have provided a measure of physiological arousal. Each block was assigned to one condition only. The four experimental conditions (0%, 30%, 70% and 100%) were determined by the probability of receiving an electric shock after the white noise offset. Every condition was indicated by a coloured geometrical shape presented as cue and was different for each condition. A green circled cued the 0% condition, a blue triangle cued the 30% condition, a yellow triangle cued the 70% condition and a red square cued the 100% condition. In the 0% condition no shock was administered, in the 30% condition the shock was administered in 30% of the trials, in the 70% condition the shock was administered in the 70% of the trials, while in the 100% condition the shock was administered in each trial. During the 30%, 70% and 100% conditions a shock was also administered at a random point during the presentation of the test arrow in 5% of the trials. The choice of intermediate probabilities was informed by (Hefner and Curtin, 2012). Their study constitutes the only study that so far has employed probabilities rather than time-related predictability in threat-of-shock paradigms. Compared to such studies, probabilities have been modified to 30% and 70% (rather than 20% and 60% in the original paper) so that 30% and 70% would have equal distance from 0% and 100%. respectively

No-memory task

Each trial began with the presentation of a cue (1000ms) that predicted the probability of receiving an electric shock at the end of the trial. The cue was followed by a 300ms blank interval. Consequently, a target arrow appeared in the upper half of the screen while a white test arrow pointing upwards was presented in the lower half of the screen. Participants were instructed to adjust the angle and colour of the test arrow in order to match them with those of the target arrow (Fig. 3.1B). Accuracy was stressed and each trial ended once a response was given.

Colour and angle of the target arrow were independently chosen at random from the same two circular parameter spaces as in the *orientation task* and the same response device was used. After the subject completed the adjustment, a 100ms long mask was displayed on

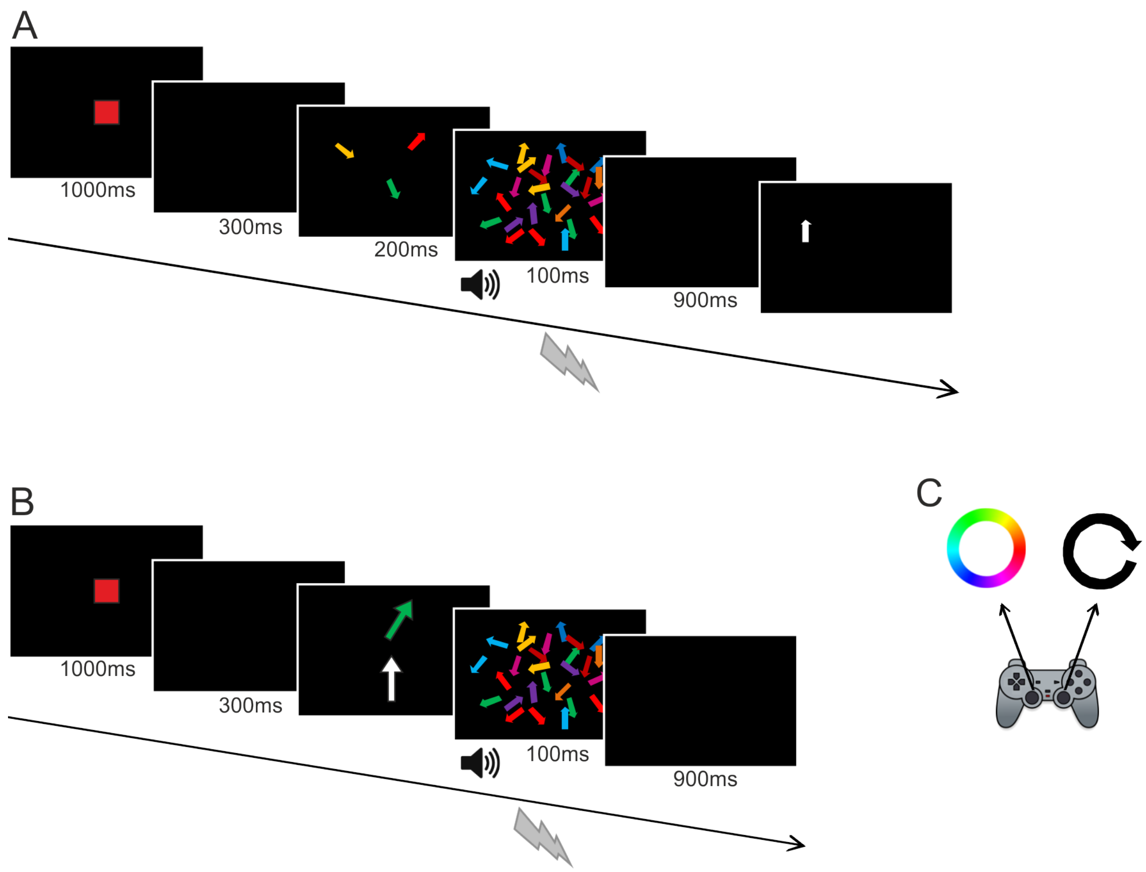

Figure 3.1 A) Example of trial in the orientation task. B) Example of trial in the no-memory task. C) Response device

the screen and was followed by 900ms of blank interval. On 12 randomly chosen trials per block, the mask onset was timed with the onset of a 102dB, 50ms long white noise presented binaurally via headphones. Immediately after the white noise offset, a 100ms electric shock was or was not administered according to the same four experimental conditions of the *orientation task*.

3.2.3 Setup, data acquisition and data analysis

All stimuli were displayed against black background on a 17-in. LCD monitor at a viewing distance of about 60-65 cm.

EMG startle reflex preprocessing

During the experiment, the EMG startle reflex was recorded using the Biopac MP150 amplifier (Biopac Systems Inc., USA). The EMG signal was continuously recorded with 4mm Ag-AgCl electrodes. Two shielded electrodes were placed on the left lower eyelid to record the activity of the *orbicularis oculi* and a third unshielded electrode was placed on the forehead. The EMG signal was sampled at 1000Hz and then smoothed with 40-500Hz FIR band-pass filter using AcqKnowledge 4.4 software (Biopac Systems Inc., USA). The signal was rectified, baseline corrected (baseline -100ms to 0ms) and averaged. For each condition, maximum peak amplitudes were identified and averaged with 2 datapoints before and after the peak. Then, values were converted first into z-scores and then in T-scores (t-score= (z*10)+50) within participants to reduce individual variability (Grillon et al., 1999). The trials where the 5% inter-stimulus shock occurred were excluded from EMG processing and analyses.

Shock administration

Electric shocks were administered on the right forearm with Biopac STM100 and STM200 stimulators. A four step workup procedure (Schmitz and Grillon, 2012) was used in order to obtain the optimal shock intensity. The participant received four test shocks starting from a minimum voltage of 10V. The participant was instructed to rate the intensity of the shock from 1 (very mild) to 5 (very unpleasant) and it was stressed that the shock should not be painful. The shock intensity was increased in steps of 5V until rate 4 was reached. If the rating of 4 was not reached after four shocks, the maximum intensity of 30V was used.

Behavioural data preprocessing

Data were analysed separately for angle and colour features. For each trial, recall errors were acquired by calculating the angular deviation between the feature value reported by the participant and the feature value of the target item (Bays et al., 2011b). The deviations were then corrected for circular responses. Maximum angle error was 180°deviation from the target value, while maximum colour error was 90°deviation from the target value.

Statistical analyses

Startle data To assess whether the probability of receiving a shock modulated the amplitude of the startle reflex, repeated-measures ANOVAs were carried out with *shock probability* as factor. If sphericity was violated, Greenhouse-Geisser corrected p-values are reported.

Next, paired-t tests Bonferroni corrected were run in case of significant ANOVAs.

Behavioural data For orientation task data, there is yet no consensus on the model that best fits this type of data. Hence, I run maximum likelihood estimation (MLE) with a Von Mises distribution, the mixed distribution proposed by the discrete-representations model (Zhang and Luck, 2008a), and the mixed distribution proposed by the probabilistic-mixture model (Bays et al., 2009).
Statistical models were defined in MATLAB as following:

```
Mises = @(x ,k) exp(k * cos(x))./(2*pi*besseli(0,k));

Mixture = @(x, k, g) g*(1/(2*pi))+(1-g)*exp(k * cos(x))./(2*pi*besseli(0,k));
```

Where:

- x is the data matrix in either the angle or colour feature
- mean is assumed 0
- k is the κ parameter of the Von Mises distribution
- g is the parameter of the uniform distribution
- besseli is the function to compute the modified Bessel function of order 0

MLE was then computed as following:

```
MLE(DataAngle, model, StartingValueForFit, lowerbound, upperbound);
```

Where:

```
lowerbound = [0 0];
upperbound = [Inf Inf];
```

The full MATLAB function `MLE()` is available in figure 3.5 in the appendix of this chapter. The estimates of the probabilistic-mixture model proposed by Bays et al. (2009) were calculated with the function `CO16_fit()` which calls the function `CO16_function()`. For the MATLAB code, see figures 3.6 and 3.7 in the appendix of this chapter.

The Akaike Information Criterion (AIC) was calculated separately for each participant and suggested that the discrete-representations model fitted the data best for both the angle and colour features in the orientation task (table 3.1 in the appendix). Repeated-measure

ANOVAs and BANOVAs were run with *shock probability* as factor and the parameters of the best fitting model as dependent variable. BANOVAs were run on R using the `BayesFactor` package (version 0.9.12-2). In the discrete-representations model, the parameter κ_t represents the variability of the behavioural response around the correct value of the target stimulus, while the parameter u represents the uniform distribution of random guesses. For no-memory data, the Von Mises distribution was fitted with the same `MLE()` function used for the data from the orientation task. In the no-memory task the stimuli consisted of a single target and no memory recall was necessary to perform the task. Given the absence of non-targets and of a memory delay period, the κ_{nt} and the u parameters of the mixture model would have increased model complexity without the theoretical justification.

The trials where the 5% inter-stimulus shock occurred were excluded from behavioural analyses.

3.2.4 Procedure

The experiment was run over two sessions of about 2.5h each carried out on two different days. Each day they completed both orientation and no-memory tasks. The order of the tasks was counterbalanced across participants. Furthermore, within participants, the task order in the two sessions was inverted. During each session, the participant completed 4 blocks of 75 trials of the orientation task and 4 blocks of 50 trials of the no-memory task.

During the first session, participants gave informed consent and then were prepared for physiological recording and shock administration following the guidelines suggested by Blumenthal et al. (2005) and Schmitz and Grillon (2012). Participants were first instructed on the first task and completed a 20 trials practice block during which there was no shock administration. Prior starting the testing, the four-steps workup procedure was carried out and the participant was habituated to the startling noise. The habituation procedure consisted presentation of 9 bursts of white noise. This procedure was employed to ensure that the strong startle habituation did not influence the results (Schmitz and Grillon, 2012). After the completion of the first task, the second task was explained, followed by a 20 trials practice block with no shock administration. The same procedure was followed during the second session.

3.3 Results

3.3.1 Orientation task

Figure 3.2 shows that EMG startle amplitude was amplified by threat of shock (F(3,48) = 14.55, $p < 0.001$, $\eta^2_G = 0.13$, $\varepsilon = 0.38$, p-value Greenhouse-Geisser adjusted). Bonferroni adjusted pairwise comparisons showed that the 30% condition (t(16) = -4.48, $p < 0.01$; M = 51.68, SD = 6.25), the 70% condition (t(16) = -4.35, $p < 0.01$; M = 53.79, SD = 6.57), and the 100% condition (t(16) = -3.05, $p < 0.05$; M = 51.73, SD = 7.13) elicited bigger amplitudes than the 0% condition (M = 56.75, SD = 7.58). Furthermore, the amplitudes in the 70% condition was bigger compared to both the 30% (t(16) = -3.90, $p < 0.01$) and the 100% conditions (t(16) = 4.61, $p < 0.01$). On the other hand, no statistically significant difference was found between the 30% and the 100% conditions.

The ANOVAs showed that precision of recall was not affected by threat of shock neither for angle nor colour in any of the parameters. For the parameter κ_t, the BF_{01} = 9.95 for angle and the BF_01 = 7.02 for colour suggest that the current data are 9.95 and 7.02 times more likely to be observed under the null hypothesis (see table 1.1 for BF interpretation). For the parameter u, the BF_{01} = 5.66 for angle and the BF_{01} = 10.88 for colour suggest that the data are 5.66 and 10.88 times more likely to be observed under the null hypothesis.

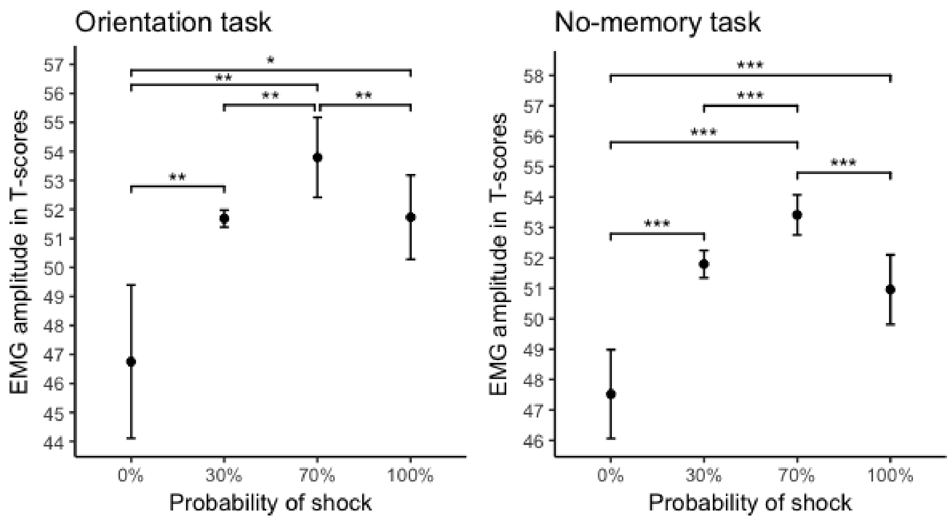

Figure 3.2 EMG startle reflex responses in the no-memory and orientation task with 95% confidence intervals. Significant contrasts are marked with asterisks (* p < 0.05, ** p < 0.01, *** p < =0.001).

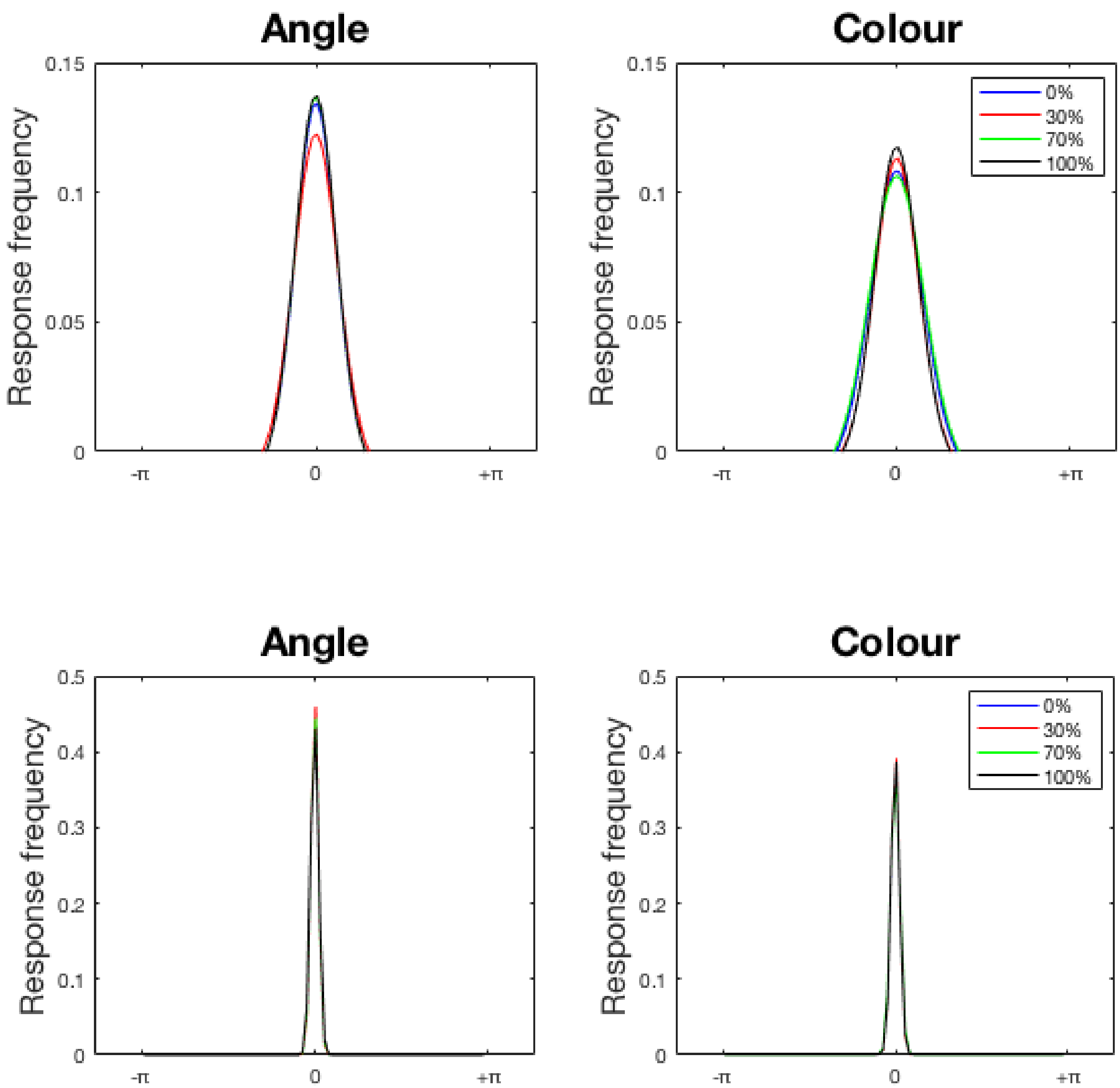

Figure 3.3 A) Fitted curves of the behavioural data in the orientation task. B) Fitted curves of the behavioural data in the no-memory task.

3.3.2 No-memory task

EMG startle amplitude was amplified by threat of shock (F(3,48) = 27.24, $p < 0.001$, $\eta_G^2 = 0.08$, $\varepsilon = 0.43$, p-value Greenhouse-Geisser adjusted). Bonferroni adjuste pairwise comparisons showed that the 30% condition (t(16) = -7.48, $p < 0.001$; M = 51.80, SD = 7.57), the 70% condition (t(16) = -6.88, $p < 0.001$, M = 53.42, SD = 6.79), and the 100% condition (t(16) = -3.36, $p < 0.05$; M = 50.96, SD = 6.13) elicited bigger amplitude than the

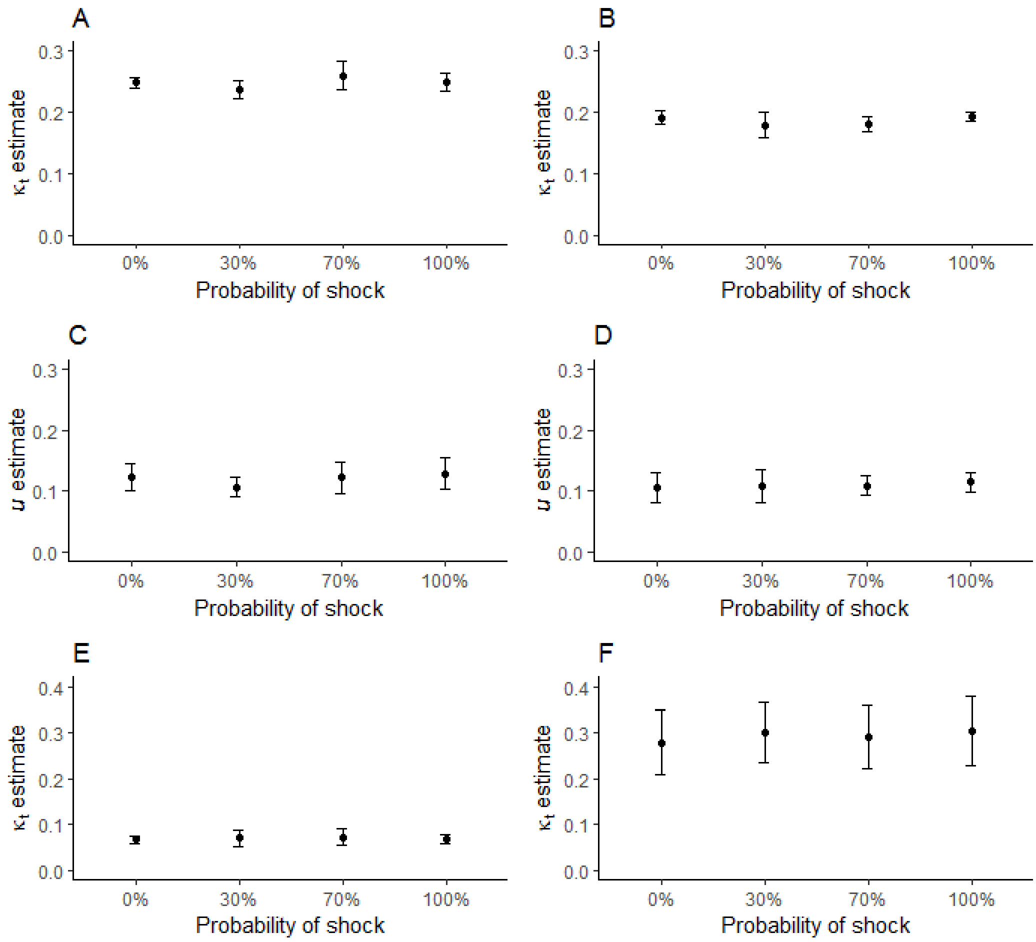

Figure 3.4 Orientation task: (A) κ_t estimates for angle data, (B) κ_t estimates for colour data, (C) u estimates for angle data, (D) u estimates for colour data. No-memory task: (E) κ_t estimates for angle data, (F) κ_t estimates for colour data. No contrast is significant. Vertical bars represent 95% confidence intervals.

0% condition (M = 47.53, SD = 8.59). Furthermore, the amplitude in the 70% condition was bigger compared to both the 30% (t(16) = -4.90, $p < 0.001$) and the 100% (t(16) = 6.84, $p < 0.001$). On the other hand, no statistically significant difference was found between the 30% and the 100% conditions (Figure 3.2).

Precision of recall was not affected by threat neither for angle nor colour. The BF_01 = 10.02 for colour suggests that the current data are 10.02 times more likely to be observed under the null hypothesis. On the other hand, the BF_01 = 2.34 for angle suggests that the support for the null hypothesis is anecdotal.

3.4 Discussion

Recently, slots models of VSWM have been challenged by resource models. According to resource models, limited resources are flexibly allocated across the set of objects to be remembered. Moreover, the different object features (e.g., colour, angle) compete for the same limited resources and the errors in recalling object features present a Gaussian-like distribution centred at the feature value (Bays et al., 2011b; Marshall and Bays, 2013; Zhang and Luck, 2008a). Precision of recall has been thought to be influenced by two factors. First, by noisy object representations caused by random fluctuations (van den Berg et al., 2012). Second, by the number of objects sharing the available attentional resources (Bays et al., 2009, 2011a; Bays and Husain, 2008). In the present study, I assessed whether anxiety may act as an external interfering factor, increasing the noise intrinsic to objects representations. To this aim, I combined the orientation task originally developed by Bays et al. (2011b) with anxiety experimentally induced by means of the NPU-threat of shock protocol (Schmitz and Grillon, 2012). Participants had to recall the angle and colour of a target arrow previously presented in a set of three arrows, while anxiety was modulated by varying the probability of receiving an electric shock. Anxiety levels were measured using the EMG ocular startle reflex, whose amplitude increases when the presence of a cue has been paired with an aversive unconditioned stimulus (Davis, 2006). Furthermore, a no-memory task that did not require memory retention, was used to assess that the effect of anxiety specifically affects memory processes. I hypothesized that the distribution of recalling errors in the orientation task would reflect anxiety interference, with larger κ_t and u parameters associated with larger interference.

3.4.1 Effect of anxiety on and physiological arousal

Anxiety measured by startle reflex amplitude was successfully modulated in both orientation and no-memory tasks. The conditions in which electric shocks were administered elicited bigger startle reflex than the control condition in which no shock was administered. Furthermore, the conditions in which the electric shock was likely to be administered elicited bigger startle reflex responses than the condition in which shock administration was certain. These results are in agreement with previous research in which uncertainty of shock administration elicited higher levels of anxiety (Grillon et al., 2004, 2008). Indeed, anxiety has been defined as a future-oriented emotional state that triggers a cascade of cognitive and physiological modifications that prepare the body to respond to threat. Uncertainty reduces individuals' predictive power over threatening events and it contributes to enhanced tension, worry, feeling of insecurity and increased physiological arousal (Barlow, 2000; Grupe and Nitschke, 2013).

Typically, uncertainty has been experimentally modulated by making the timing of shock administration unpredictable, as reported in the NPU-threat test protocol of Schmitz and Grillon (2012). However, in the present study we adopted a modified approach, modulating uncertainty in terms of probability of shock (Hefner and Curtin, 2012). Such approach was chosen because varying the timing of the shock (rather than the probability) would have meant to apply a shock at each single trial. Given the necessity of a large number of trials for statistical analysis of behavioural data, variations in probability was chosen to reduce discomfort for the participants.

As it may be noted, the standard deviations vary a lot with probability of shock. In particular, the standard deviation is considerably bigger for the 0% condition. I could hypothesize that in such condition the variability across participants may reflect big individual variability in the response to a testing situation. On the other hand, during shock administration, participants might activate a physiological fight-or-flight fear response that is evolutionary advantageous and therefore more stereotyped.

3.4.2 Effect of anxiety on behavioural data

In the present study, three statistical models were fitted to the data in both orientation and no-memory tasks. In the orientation task, the discrete-representation model had the best fit of the behavioural data (both for colour and angle data) against the competing models: the simple Von Mises distribution and the probabilistic-mixture model proposed by Bays et al. (2009) (Table 3.1). I therefore looked at whether anxiety affected the error distribution parameters. Unsurprisingly, anxiety did not modulate error distribution in the no-memory task and precision of response was very high (Fig. 3.3). Such effect was expected as the no-memory task did not have a retention period in which representations could have been subject to interference. On the other hand, I expected the effect of anxiety in the behavioural data of the orientation task. However, anxiety had an effect on response precision in neither colour nor angle features. If anxiety affected the κ_t parameter, I could argue that anxiety might have depleted the available attentional resources and decreased precision of recall. One explanation might have stemmed from the framework of the Attentional Control Theory (Eysenck et al., 2007, 2005) according to which anxiety reduces resistance to distractors by redirecting attention towards threatening stimuli (Eysenck et al., 2007). Hence, threat of shock would have reduced the available limited attentional resources needed to discern between competing internal representations. An alternative explanation would have been that anxiety acted as a source of noise. The reduction in recall precision would have not been a result of depletion of resources, but rather the result of the increased instability of internal representations. Fougnie et al. (2012) have suggested that memory representations are subject to a stochastic process of degradation stemming from physiological cortical noise. It is known that networks supervising anxious arousal overlap with networks associated with spatial attention and WM, such as the prefrontal cortex (Adhikari et al., 2010; Dalton et al., 2005; Manoach et al., 2004). It has been shown that during anxious states changes in connectivity between prefrontal and limbic areas reduces emotional control of memory and attentional processes (Gilboa et al., 2004; Gold et al., 2015; Prater et al., 2013). If the recruitment of larger neural population improved the precision of WM representations through decreased signal drift, a reduction in the emotional control over prefrontal areas might have increased cortical noise and therefore reduced representation acuity. This explanation is however hypothetical and would need extensive testing. Finally, if anxiety affected the u parameter, we could have argued that anxiety increased random guesses rate. Reducing the number of items encoded. This explanation would have been in agreement with the evidence that suggests that both state and trait anxiety reduces WM capacity (Ashcraft and Kirk, 2001; Eysenck and Calvo, 1992; Sorg and Whitney, 1992). It seems unlikely that worry would have reduced VSWM capacity in the present task because anxiety was induced by means of threat of shock. On the other hand, we could have argued that the probability of shock activated stimulus-driven attentional processes at the expense of task-driven allocation of resources.

Here, I elaborated on how anxiety could have impacted VSWM taking into account the framework of the model that best fitted the data. However, the empirical results of the present study pointed towards the absence of an anxiety effect on precision data (Fig. 3.4). According to the results obtained by frequentist statistics, I could not reject the null hypothesis. Therefore, no conclusion could be drawn. However, the BANOVAS suggested that the data are most likely to be observed under the null hypothesis. In the orientation task, the evidence for the absence of an effect of anxiety was substantial for the parameter κ_t for angle and colour data, and for the parameter u for angle data. Furthermore, evidence for the null hypothesis was strong for the u parameter in colour data of the orientation task and for the κ_t parameter of colour data in the no-memory task. On the other hand, the evidence for the null hypothesis in the no-memory angle data was only anecdotal.

Drawing conclusions on the resilience of VSWM to anxiety is at this stage premature. However, it is possible to make preliminary hypotheses on why the anxiety manipulation did not have any impact on response precision. One possibility is that the detrimental effect of anxiety were overcome by compensatory mechanisms, resulting in no behavioural differences between conditions. Several studies have shown the benefits of compensatory strategies on behavioural performance. For example, in a backward digits span task children with high and low state anxiety did not differ in performance. However, the high anxiety group took longer to perform the task and reported increased mental effort (Hadwin et al., 2005). In another study, high and low maths anxious participants did not differ in the performance to a maths task. However, the high anxious group showed enhanced ERP components associated with increased engagement of cognitive resources (Suárez-Pellicioni et al., 2013). Therefore, it is plausible that in the present task the detrimental effect of anxiety was compensated by the increased allocation of cognitive resources. A second factor might have been the means by which anxiety has been manipulated. It is known that sources of anxiety can be diverse. Indeed, anxiety can be elicited in healthy patients by task-irrelevant manipulations, such as threat of shock (Schmitz and Grillon, 2012) and CO_2-enriched air inhalation (Bailey et al., 2005; Poma et al., 2005; Woods et al., 1988). The threat of shock paradigm used in the present study has the advantage of being a well established technique that reliably produces anxious physiological arousal. Furthermore, by modifying the probability of shock, such technique can be used in block designs allowing within-participants investigations. However, a drawback might be that the threatening stimulus is completely task-irrelevant and may not suited to investigate the cognitive interference of anxiety. According to the ACT (Eysenck et al., 2007) anxiety disrupts the WM inhibition function by external task-irrelevant stimuli but also by internal task-irrelevant stimuli such as worry. It is possible that in the present paradigm the nature of the threatening stimuli did not initiate worry and self preoccupation as, for example, fear of failure could do in a maths test situation. Hence, anxiety might not have taken a toll on cognitive control despite inducing increased physiological arousal. Furthermore, the placement of the shock delivery within the trial might not have been ideal. The choice of delivering the shock before target presentation was made so that anxiety was high during the retention period. While participants were not informed on when they would receive a shock within the trial, the timing of shock delivery was kept constant. Hence, participants might have implicitly understood that if a shock was not delivered after a certain time, then they would be safe. For the same reason, we did not make the choice of delivering the shock after a response was given. This would have created a safe space during the retention interval, with the risk of minimizing the effects of the induced anxiety. A third factor influencing the outcome of the present study might be the set size of the trials. Because of constraints dictated by time (the participants completed two sessions of 2.5 hours each) we only employed a set size of three items. One of the primary findings in the literature is that variability of recall increases with set size (Ma et al., 2014). Because the relationship between precision of recall and set size seems to follow a simple power law (Bays et al., 2009; Bays and Husain, 2008) set size 3 has been chosen arbitrarily. It is possible that the cumulative noise of the items composing the experimental trials was not sufficient for anxiety to have a behavioural observable effect on recall precision.

3.4.3 Directions for future research

The results reported in this study leave us with more open questions than answers. Before ruling out any effect of anxiety on parameters describing resource models of VSWM, it should be investigated whether other factors have influenced the outcome. First, the same experiment could be run on increased set sizes. However, adding set sizes in the repeated measure design with four condition would be not feasible because it would require too much testing time. One option would be dropping the 30% and 100% probability of shock conditions as they provide redundant information. Because the 70% condition was the most successful in eliciting anxiety, reducing the conditions to 0% and 70% would allow to include set size as a second factor in the design. Second, timing of shock could be varied in order to ensure that anxiety is high during the retention period. Third, it might have been that threat of shock did not elicit sufficient anxiety to produce a detectable behavioural effect. To overcome this issue it may be interesting to see if highly anxious individuals do show any behavioural effect of anxiety on precision of recollection. Finally, electroencephalography could be used to assess whether compensatory strategies have come into play. For example, the same task could be run while measuring ERPs. Analysing components that reflect cognitive effort and the recruitment of processing resources such as the P300 and the Late Positive Component (Polich, 2007) could offer an insight into compensatory activity. Differences in such components in conjunction to no behavioural effects would be an indication that anxiety depletes attentional resources and requires increased cognitive effort in order to produce the same behavioural performance.

3.5 Conclusions

In summary, the aim of the present study was to assess whether anxiety impacts precision of recall. To this aim we manipulated anxiety using threat of shock in healthy participants and asked them to replicate the angle and colour of a target arrow previously displayed. We then compared across conditions the parameters of a mixed distribution (Zhang and Luck, 2008a). The results in both the angle and colour feature of the stimuli point towards an absence of the effect of anxiety on behavioural data. Both the distribution parameter expressing response precision and random guessing were not affected by the experimental manipulation.

3.6 Declaration

The experiment carried out in the present chapter is my original work. The `MLE()` MATLAB function and sections of the code used for model fitting were written with the help of Dr Dénes Szűcs.

3.7 Appendix

```
function [maxLikelihood, like] = MLE(data, pdf,StartingValueForFit,lowerb,upperb)

logpdf = @(varargin)(nansum(log(pdf(varargin{:}))));

options = statset('MaxIter',2e6,'MaxFunEvals',2e6,...
    'UseParallel','always','FunValCheck','off');

% Start the search at several different points (based on StartingValueForFit)
numChains = size(StartingValueForFit,1);
like = zeros(numChains,1);
vals = cell(numChains,1);
for c=1:numChains
    % Maximize the likelihood function
    vals{c} = mle(data, 'logpdf', logpdf, 'start', StartingValueForFit(c,:), ...
        'lowerbound', lowerb, 'upperbound', upperb, ...
        'options', options);

    % Store MLE values
    asCell = num2cell(vals{c});
    like(c) = logpdf(data, asCell{:});
end

% Combine values across chains
likeSamples.vals = [vals{1}];
likeSamples.like = like;
for c=2:numChains
    likeSamples.vals = [likeSamples.vals; vals{c}];
end

% Find MLE estimate (best one across all the chains)
[like,b]=max(likeSamples.like);
maxLikelihood = likeSamples.vals(b,:);
end
```

Figure 3.5 The MATLAB code reports the function used to estimate the parameters of the model with maximum likelihood estimation.

```
function [B, LL, W] = CO16_fit (X, T, NT)
% CO16_FIT (X, T, NT)
%   Returns maximum likelihood parameters B for a mixture model describing
%   recall responses X in terms of target T, non-target NT, and uniform
%   responses. Inputs should be in radians, -PI <= X < PI. Fitting is based
%   on an EM algorithm with multiple starting parameters.
%
%   B = CO16_FIT (X, T, NT) returns a vector [K pT pN pU], where K is
%   the concentration parameter of a Von Mises distribution capturing
%   response variability, pT is the probability of responding with the
%   target value, pN the probability of responding with a non-target
%   value, and pU the probability of responding "randomly".
%
%   [B LL] = CO16_FIT (X, T, NT) additionally returns the log likelihood LL.
%
%   [B LL W] = CO16_FIT (X, T, NT) additionally returns a weight matrix of
%   trial-by-trial posterior probabilities that responses come from each of
%   the three mixture components. Each row of W corresponds to a separate
%   trial and is of the form [wT wN wU], corresponding to the probability
%   the response comes from the target, non-target or uniform response
%   distributions, respectively.
%
%   Refs:
%   Schneegans S & Bays PM. No fixed item limit in visuospatial working
%   memory. Cortex 83: 181-193 (2016)
%
%   Bays PM, Catalao RFG & Husain M. The precision of visual working
%   memory is set by allocation of a shared resource. Journal of Vision
%   9(10): 7, 1-11 (2009)

n = size(X,1);

if (nargin<2) T = zeros(n,1); end

if (size(X,2)>1 || size(T,2)>1 || size(X,1)~=size(T,1)...
        || nargin>2 && ~isempty(NT) && (size(NT,1)~=size(X,1)...
        || size(NT,1)~=size(T,1)))
end
    error('Input is not correctly dimensioned'); return;
end

if (nargin<3) NT = zeros(n,0); nn = 0; else  nn = size(NT,2); end

% Starting parameters
K = [      1    10   100];
N = [   0.01   0.1   0.4];
U = [   0.01   0.1   0.4];

if nn==0, N = 0; end

LL = -inf; B = [NaN NaN NaN NaN]; W = NaN;
```

```
warning('off','JV10_function:MaxIter');

% Parameter estimates

for i=1:length(K)
    for j=1:length(N)
        for k=1:length(U)
            [b ll w] = CO16_function(X,T,NT,[K(i) 1-N(j)-U(k) N(j) U(k)]);
            if (ll>LL)
                LL = ll;
                B = b; W = w;
            end
        end
    end
end

warning('on','JV10_function:MaxIter');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Copyright 2017 Paul Bays. This program is free software: you can     %
%   redistribute it and/or modify it under the terms of the GNU General  %
%   Public License as published by the Free Software Foundation.         %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Figure 3.6 The MATLAB code reports the `CO16_fit()` function used to fit the probabilistic-mixture model. The function calls the `CO16_function()` function (see Fig. 3.7). The function is downloadable from www.paulbays.com

```
function [B, LL, W] = C016_function (X, T, NT, B_start)

if (nargin<2 || size(X,2)>1 || size(T,2)>1 || size(X,1)~=size(T,1)...
        || nargin>2 && ~isempty(NT) && (size(NT,1)~=size(X,1)...
        || size(NT,1)~=size(T,1)))
end
    error('Input is not correctly dimensioned');
    return;
end

if (nargin>3 && (B_start(1)<0 || any(B_start(2:4)<0) || any(B_start(2:4)>1)...
        || abs(sum(B_start(2:4))-1) > 10^-6))
    error('Invalid model parameters');
    return;
end

MaxIter = 10^4; MaxdLL = 10^-4;

n = size(X,1);

if (nargin<3)
    NT = zeros(n,0); nn = 0;
else
    nn = size(NT,2);
end

% Default starting parameters
if (nargin<4)
    K = 5; Pt = 0.5;
    if (nn>0) Pn = 0.3; else Pn = 0; end
    Pu = 1-Pt-Pn;
else
    K = B_start(1);
    Pt = B_start(2); Pn = B_start(3); Pu = B_start(4);
end

E  = X-T; E = mod(E + pi, 2*pi) - pi;
NE = repmat(X,1,nn)-NT; NE = mod(NE + pi, 2*pi) - pi;


LL = nan; dLL = nan; iter = 0;

while (1)
    iter = iter + 1;

    Wt = Pt * vonmisespdf(E,0,K);
    Wg = Pu * ones(n,1)/(2*pi);

    if nn==0
        Wn = zeros(size(NE));
    else
        Wn = Pn/nn * vonmisespdf(NE,0,K);
```

```
    end

    W = sum([Wt Wn Wg],2);

    dLL = LL-sum(log(W));
    LL = sum(log(W));
    if (abs(dLL) < MaxdLL | iter > MaxIter) break; end

    Pt = sum(Wt./W)/n;
    Pn = sum(sum(Wn,2)./W)/n;
    Pu = sum(Wg./W)/n;

    rw = [(Wt./W) (Wn./repmat(W,1,nn))];

    S = [sin(E) sin(NE)]; C = [cos(E) cos(NE)];
    r = [sum(sum(S.*rw)) sum(sum(C.*rw))];

    if sum(sum(rw))==0
        K = 0;
    else
        R = sqrt(sum(r.^2))/sum(sum(rw));
        K = A1inv(R);
    end

    if n<=15
        if K<2
            K = max(K-2/(n*K), 0);
        else
            K = K * (n-1)^3/(n^3+n);
        end
    end
end

if iter>MaxIter
    warning('JV10_function:MaxIter','Maximum iteration limit exceeded.');
    B = [NaN NaN NaN NaN]; LL = NaN; W = NaN;
else
    B = [K Pt Pn Pu]; W = bsxfun(@rdivide,[Wt sum(Wn,2) Wg],W);
end
```

```
function K = A1inv(R)

if (0 <= R & R < 0.53)
    K = 2 * R + R^3 + (5 * R^5)/6;
elseif (R < 0.85)
    K = -0.4 + 1.39 * R + 0.43/(1 - R);
else
    K = 1/(R^3 - 4 * R^2 + 3 * R);
end
function p = vonmisespdf (x, mu, K)

p = exp(K.*cos(x-mu) - log(2*pi) - besseliln(0,K));
```

```
function w = besseliln(nu,z)

w = log(besseli(nu,z,1))+abs(real(z));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Copyright 2017 Paul Bays. This program is free software: you can     %
%   redistribute it and/or modify it under the terms of the GNU General  %
%   Public License as published by the Free Software Foundation.         %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Figure 3.7 The MATLAB code reports the `C016_function()` function. The function is downloadable from www.paulbays.com

	0% shock			30% shock			70% shock			100% shock		
	Von Mises	DRM	PMM	Von Mises	DRM	PMM	Von Mises	DRM	PMM	Von Mises	DRM	PMM
ANGLE	-377.0	-412.0	-410.0	-336.0	-384.0	-382.0	-388.0	-401.0	-399.0	-354.0	-408.0	-406.0
	-63.9	-165.0	-163.0	-81.5	-140.0	-138.0	-107.0	-196.0	-194.0	-157.0	-286.0	-284.0
	-87.5	-157.0	-155.0	-90.0	-168.0	-166.0	-136.0	-179.0	-177.0	-82.3	-99.7	-97.7
	-222.0	-324.0	-322.0	-171.0	-273.0	-271.0	-259.0	-357.0	-355.0	-170.0	-232.0	-230.0
	-26.3	-165.0	-163.0	30.1	-85.0	-83.0	0.429	-90.8	-88.8	-38.6	-194.0	-192.0
	-311.0	-372.0	-370.0	-200.0	-293.0	-291.0	-249.0	-302.0	-300.0	-284.0	-348.0	-346.0
	-76.9	-180.0	-178.0	-53.8	-201.0	-199.0	-77.0	-212.0	-210.0	-1.61	-129.0	-127.0
	-186.0	-339.0	-337.0	-24.0	-221.0	-219.0	80.8	-104.0	-102.0	-132.0	-279.0	-277.0
	-211.0	-327.0	-325.0	-193.0	-283.0	-281.0	-231.0	-283.0	-281.0	-322.0	-393.0	-391.0
	-78.9	-186.0	-184.0	-51.8	-193.0	-191.0	-76.3	-190.0	-188.0	-4.16	-132.0	-130.0
	-97.8	-249.0	-247.0	-128.0	-240.0	-238.0	-118.0	-235.0	-233.0	-17.6	-134.0	-132.0
	-3.9	-47.2	-45.2	-2.36	-114.0	-112.0	-44.1	-120.0	-118.0	-30.7	-143.0	-141.0
	-2.2	-114.0	-112.0	38.6	-63.3	-61.3	-6.63	-83.7	-81.7	-17.5	-106.0	-104.0
	-25.4	-124.0	-122.0	-37.2	-132.0	-130.0	-3.77	-126.0	-124.0	-64.6	-134.0	-132.0
	-183.0	-245.0	-243.0	-198.0	-262.0	-260.0	-243.0	-335.0	-333.0	-199.0	-281.0	-279.0
	-45.9	-156.0	-154.0	5.75	-85.1	-83.1	-46.2	-127.0	-125.0	-79.8	-154.0	-152.0
	-127.0	-203.0	-201.0	-147.0	-275.0	-273.0	-131.0	-249.0	-247.0	-128.0	-224.0	-222.0

	0% shock			30% shock			70% shock			100% shock		
	Von Mises	DRM	PMM	Von Mises	DRM	PMM	Von Mises	DRM	PMM	Von Mises	DRM	PMM
COLOUR	-179.0	-299.0	-297.0	-95.8	-173.0	-171.0	-106.0	-211.0	-209.0	-152.0	-249.0	-247.0
	110.0	-80.0	-78.0	65.9	-161.0	-159.0	87.7	-113.0	-111.0	-26.7	-235.0	-233.0
	40.5	-104.0	-102.0	-3.61	-224.0	-222.0	50.1	-58.9	-56.9	-15.5	-176.0	-174.0
	-167.0	-265.0	-263.0	-150.0	-285.0	-283.0	-165.0	-233.0	-231.0	-116.0	-225.0	-223.0
	17.1	-191.0	-189.0	5.27	-176.0	-174.0	24.9	-117.0	-115.0	5.97	-95.9	-93.9
	-281.0	-327.0	-325.0	-304.0	-356.0	-354.0	-304.0	-340.0	-338.0	-314.0	-353.0	-351.0
	-98.7	-208.0	-206.0	27.7	-86.0	-84.0	-6.01	-211.0	-209.0	-17.5	-175.0	-173.0
	-197.0	-278.0	-276.0	-18.8	-139.0	-137.0	33.2	-60.9	-58.9	-133.0	-217.0	-215.0
	-27.2	-164.0	-162.0	-20.8	-180.0	-178.0	-26.9	-171.0	-169.0	-48.9	-221.0	-219.0
	-39.2	-156.0	-154.0	24.4	-103.0	-101.0	-63.7	-253.0	-251.0	-18.0	-201.0	-199.0
	-34.4	-152.0	-150.0	-94.0	-211.0	-209.0	-103.0	-204.0	-202.0	-84.6	-210.0	-208.0
	101.0	-38.9	-36.9	53.2	-143.0	-141.0	43.6	-135.0	-133.0	10.5	-77.0	-75.0
	54.2	-234.0	-232.0	31.7	-215.0	-213.0	74.2	-207.0	-205.0	38.9	-195.0	-193.0
	53.6	-173.0	-171.0	109.0	-37.5	-35.5	91.1	-170.0	-168.0	87.1	-144.0	-142.0
	-162.0	-308.0	-306.0	-168.0	-258.0	-256.0	-133.0	-250.0	-248.0	-148.0	-251.0	-249.0
	32.7	-135.0	-133.0	58.9	-115.0	-113.0	28.7	-226.0	-224.0	-5.5	-232.0	-230.0
	-51.4	-218.0	-216.0	-129.0	-241.0	-239.0	-108.0	-232.0	-230.0	-49.9	-174.0	-172.0

Table 3.1 Akaike Information Criterion values calculated for single participants on orientation task data. The Von Mises model, the descrete-representations model (DRM) and the probabilistic-mixed model (PMM) were fitted to the data. The Akaike Information Criterion informed on which model fitted the data best. Lower values indicate better fit.

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Chapter 4

Implicit and explicit measures of maths anxiety

4.1 Introduction

4.1.1 MA as a complex construct

MA is a complex construct in which cognition, metacognition, physiology and performance are tightly interconnected and their individual role is still under scientific investigation. The complexity of such construct becomes apparent when investigating the relationship between MA and performance to maths tasks. It is indeed still debated whether difficulties in maths are the primary cause of MA or whether is MA playing a role in poor maths performance (Carey et al., 2016). Studies investigating poor maths skills in children have suggested that children with early maths learning disabilities or other cognitive deficits, such as poor self-regulation skills, report higher levels of MA (Jain and Dowson, 2009; Kramarski et al., 2010; Passolunghi, 2011; Rubinsten and Tannock, 2010). Furthermore, longitudinal studies on schooling populations have found a correlation between maths achievement and MA scores the following year (Ma and Xu, 2004). While these studies seem to suggest that cognitive deficits and poor maths performance are the cause of MA, Devine et al. (2013) reported that only a small percentage of the population is diagnosed with specific learning disabilities (1-6% in the case of dyscalculia). Given that the prevalence of MA has been reported to be between 6% to 68%, depending on population and inclusion criteria (Dowker et al., 2016), it is unlikely that the entirety of the prevalence is explained by cognitive disabilities. Furthermore, Devine et al. (2017) found that 77% of their sample had high MA but typical maths performance. Suggesting that emotional maths difficulties and cognitive maths difficulties dissociate.

Others suggest an opposite relationship, with MA impairing maths performance. It has been hypothesized that the mechanism through which MA impacts performance is by depleting cognitive resources, as explained by the ACT (Eysenck and Calvo, 1992). Like in the case of other types of anxiety, MA individuals during a maths task may experience worry. Worry consists of self-directed and task-irrelevant thoughts that may reduce WM resources. The role that the different WM components (Baddeley, 1992) have in arithmetic processing has been object of wide investigation (for reviews, see DeStefano and LeFevre, 2004; Raghubar et al., 2010). It is therefore not surprising that researchers have hypothesized that the effects of MA on maths performance may be mediated by the effects on WM resources. For example, HMA participants have been found to have reduced WM spans compared to LMA participants (Ashcraft and Kirk, 2001; Ashcraft and Krause, 2007) and differences in WM have been found to be a significant factor accounting for the variance in maths performance in HMAs (Miller and Bichsel, 2004). Furthermore, Mattarella-Micke et al. (2011) found that the impact that MA had on maths performance was mediated by WM capacity. On the other hand, Klados et al. (2015) have reported differences between HMAs and LMAs in the cortical activation of areas associated with WM independently of performance. Finally, studies have observed that modulating MA either by increasing social pressure (Gerstenberg et al., 2012; Marx et al., 2013; Seitchik et al., 2014; Spencer et al., 1999a) or by modifying task properties, such as the time available to perform the task (Faust et al., 1996), had an effect on performance.

4.1.2 The importance of implicit measures of MA

There is not yet consensus on the directionality of the relationship between MA and performance and the mechanisms through which such relationship is regulated. MA is a complex construct that is influenced by phenomena that span from social pressure to basic cognitive processes. Hence, measuring MA is a challenging task. MA is typically measured by self-report questionnaires in which individuals rate their agreement or disagreement on a series of sentences referring to everyday situations involving maths. These questionnaires have satisfactory psychometric properties (Alexander and Martray, 1989; Carey et al., 2017; Hopko et al., 2003a; Plake and Parker, 1982; Richardson and Suinn, 1972). However, they are subject to general limitations linked to the fact that they are *explicit measures* of anxiety. First, questionnaires assume that individuals are honest in their answers. This might be problematic especially in studies investigating gender differences. For example, the stereotype that boys are better at maths than girls (Spencer et al., 1999b) might result in girls being more willing to report difficulties in maths related tasks than boys. Unfortunately, the tools available do not provide any scale enabling questionnaire invalidation where biased answers are detected. Second, self-report measures require a certain level of metacognition that might differ between ages, genders and abilities. Third, scores are not easily comparable between culturally and linguistically different samples. Furthermore, as reported in the previous section, MA also impact basic cognitive processes such as WM that are engaged in an automatized fashion and are only partially, if at all, under the control of conscious top-down processes. There is therefore a qualitative discrepancy between *explicit measures* and the processes impacted by MA. Explicit measures quantify MA through a verbal output that is the result of a process of self-evaluation. On the other hand, the cognitive processes impacted by MA are automatized in nature. Hence, interest has grown for *implicit measures*. Implicit measures seek to quantify automatised cognitive processes and physiological indices that are modulated by MA.

4.1.3 The affective priming task as a behavioural implicit measure of MA

Behavioural measures have been employed to investigate automatised processes (Hopko et al., 1998, 2002; Rubinsten et al., 2015; Rubinsten and Tannock, 2010; Suárez-Pellicioni et al., 2015). One task that has been implemented to study the emotional value that the subjects attribute to stimuli is the affective priming task. The idea behind the affective priming task is that participants respond quicker to stimuli that are emotionally congruent with the preceding prime (Fazio et al., 1986; Houwer et al., 2002). There are two mechanisms that have been suggested to underlie such effect. According to the *spreading of activation* account (Collins and Loftus, 1975), concepts are organized as nodes in semantic networks. Nodes that share similar valence are linked to each other. If a node is activated (for example by a priming word with a certain valence) the activation spreads to the neighbouring nodes. If response selection depends on node activation, the nodes that have been activated because linked to the prime will elicit a faster response compared to nodes that do not share strong links with the prime (Fazio, 2001). On the other hand the *response activation account* explains affective priming effects in terms of response selection, rather than target evaluation. According to this account, the prime stimuli activate responses on the basis of their valence (positive or negative). For example, if subjects are asked to judge if a target word is positive or negative (e.g. *beautiful*), response selection will be faster if the preceding prime had positive valence as well (e.g. a smiley face). Because the prime will have activated a positive response, the subject will be facilitated to select a response that is congruent with the valence of the prime (De Houwer et al., 2009).

Rubinsten and Tannock (2010) used an affective priming task paired with an arithmetic verification task to study MA in children with developmental dyscalculia (DD). Specifically, they looked at how priming words influence the processing of mental arithmetic in DD children. They used prime words that could either be positive, negative, neutral or related to maths (such as *quantity*). Words were followed by an arithmetic operation that the subject had to judge whether it was correct or incorrect. They found that DD children responded faster when the operation was preceded by negative prime words. On the other hand, controls responded faster when the operations were preceded by positive prime words. No difference was found between responses to trials with maths-related and neutral primes. Because affective prime words facilitate responses to targets that are emotionally congruent, the authors concluded that DD children attributed negative valence to maths. The same task was used in Rubinsten et al. (2012) to assess whether gender differences in the ability to solve arithmetic facts depend on differences in MA. An affective priming effect was found in both groups but with different directionality. Males had responded faster when the operations were preceded by positive prime words. On the other hand, females were faster when the operations were preceded by negative prime words. Hence, the authors concluded that males attribute positive valence to maths while females attributed negative valence. The authors suggested that the priming effect may be due to differences in MA. Therefore the affective priming task may be an implicit measure of MA.

4.1.4 The startle reflex and HRV as physiological implicit measures of MA

Because of the automatised nature of physiological reactions to stress, several studies have attempted to investigate MA by means of physiological indices with varying success (as reported in the general introduction). The measure that seems to be the most effective in measuring MA is salivary cortisol (Mattarella-Micke et al., 2011; Pletzer et al., 2010; Sarkar et al., 2014). However, the fact that changes in cortisol levels reflect an hormonal response makes it difficult to pair it with computerised tasks that are usually employed to investigate cognitive processes. First, the time lag between psychological responses and endocrine responses (Hellhammer et al., 2009; Schlotz et al., 2008; Smyth et al., 1998) makes cortisol measurements suitable for paradigms that require a small number of measurements spaced in time (e.g. before and after a maths exam). However, it is less suitable to be used in conjunction with tasks that require fast online measurements. This is the case for computerised tasks with fast presentation of stimuli and within-participants design. Second, salivary cortisol spontaneously varies throughout the day, making it difficult to compare levels across participants (Gröschl et al., 2003).

Physiological measures that have faster reactivity to stressors are the ocular startle reflex and HR measures. As mentioned in the general introduction, the ocular startle reflex has widely been used to assess the physiological arousal during anxious states (Davis, 2006; Grillon et al., 1991; Grillon and Davis, 1997). However, to the best of my knowledge it has never been employed to assess MA. Regarding HR measures, the literature investigating the sensitivity of HR (measured as beats-per-minute) to MA levels has produced inconsistent results (Dew et al., 1984; Hopko et al., 2005, 2003b). Whether heart rate increases or decreases in anticipation of threatening stimuli is still debated (Alm, 2004). Inconsistency in HR results might be due to the fact that during anxious responding the sympathetic and the parasympathetic branches of the autonomic nervous system coactivate exerting opposite effects on the heart rate. Therefore, measures of HRV may be more suitable for the assessment of anxiety (Chalmers et al., 2014; Shaffer et al., 2014). Similarly to the startle reflex, to the best of my knowledge HRV has not been used to assess MA.

4.1.5 Rationale of the study

The aim of the present study was to investigate implicit measures of MA. I adopted the same affective priming task paired with a verification task developed by Rubinsten and Tannock (2010) and replicated by Rubinsten et al. (2012), recording the startle reflex and HRV data. The priming task consisted in the presentation of emotionally charged words followed by an arithmetic verification task. The purpose of the task was to test the behavioural and physiological response to the association between the emotional valence of the prime words and the emotional valence attributed to performing maths. Furthermore, a two-back task with geometrical figures was administered. Participants had to judge whether the current stimulus was the same as the one presented two trials earlier. The aim of the two-back task was to assess how variations in HRV measures could be attributed to WM load regradless of emotional valence. Regarding HRV measures, the mean of the IBIs was selected as simple time-domain measure, the SDNN and the RMSSD as complex time-domain measures and the ratio LF/HF as frequency domain measure.

From the present experiment, I first expected to replicate the affective priming effects: participants with higher levels of MA were expected to respond faster to negative compared to positive prime trials. On the other hand, I did not expect prime effects on neutral and maths trials as in Rubinsten and Tannock (2010) and Rubinsten et al. (2012). Second, I expected to observe larger startle reflexes and reduced HRV in HMAs. Third, I aimed at assessing whether the effects of MA on the affective priming task showed a corresponding activation in physiological measures. I expected that HMAs showed larger startle reflex and smaller HRV in trials preceded by negative words than in trials preceded by positive words. I did not have strong hypotheses regarding trials preceded by negative and maths primes. Finally, I wanted to assess whether implicit measures of MA predicted self-report ratings.

4.2 Materials and methods

4.2.1 Participants

60 participants were tested. 40 participants (11 M, 29 F, mean age 24.44, mean education was Master's degree) were retained for the analysis (see sections 4.2.2 and 4.2.5 for details on inclusion criteria). Participants were over 18 years of age, English native speakers, did not have a history of psychiatric disorders or learning disabilities and had normal or corrected-to normal vision and hearing.

Participants were recruited via the University bulletin and paid £20 for their participation. The study was approved by the Psychology Research Ethics Committee of the University of Cambridge.

4.2.2 Tests and self-report measures

Numeracy skills were tested with an arithmetic difficulties questionnaire (Openhaim-Bitton, 2003). In this test participants had 2 minutes to solve as many operations as possible (see fig. 4.6 in the appendix of this chapter). Operations had to be solved in order without being skipped. One participant scored 3 SD below the mean and was excluded from the analysis. Reading skills were assessed with the WIAT-II Reading Task (starting from section C) in which participants were asked to read aloud a list of words whose pronunciation increased in difficulty. No participant scored more than 1 SD below the mean in the total raw score. The State-Trait Anxiety Inventory (STAI-state and STAI-trait) and Test Anxiety Inventory (TAI) questionnaires were also administered (Spielberger, 1977; Spielberger et al., 1983). MA was assessed using the Abbreviated Maths Anxiety Scale (AMAS Alexander and Martray, 1989).

4.2.3 Tasks and stimuli

Verification task with emotional priming

The participants performed a verification task combined with affective priming. The stimuli appeared in white against a black background and were displayed at the centre of a 17-inch Apple LCD monitor placed about 50 cm in front of the participants.

Priming was induced by means of written words. A total of 40 word primes were chosen as belonging to four different types (table 4.1): 10 with negative emotional value, 10 with positive emotional value, 10 with neutral emotional value and 10 maths related. Of these, 33 were selected from the Affective Norms for English Words database (ANEW; Bradley and Lang, 1999). In the database, words are rated in their valence (ranging from *pleasant* to *unpleasant*), arousal (ranging from *calm* to *excited*) and dominance (ranging from *in control* to *dominated*). In the current study, all words selected had low arousal (scores from 1 to 3 in the arousal dimension) and medium dominance (scores from 4 to 6 in the dominance dimension). In the valence dimension, negative primes were rated 1 to 3, neutral primes were rated 4 to 6, and positive primes were rated 7 to 9. Because the ANEW did not have enough maths word, 7 maths words were selected outside of the database. All four word types had an average length of 4.6 letters per word.

	Prime	**Valence**	**Freq.**	**Length**		**Prime**	**Valence**	**Freq.**	**Length**
Positive	bed	7.51	127	3	Neutral	door	5.16	312	4
	bird	7.27	31	4		chair	5.08	66	5
	gentle	7.31	27	6		chin	5.29	27	4
	peace	7.72	198	5		elbow	5.12	10	5
	relax	7.00	14	5		arm	5.34	94	3
	safe	7.07	58	4		lamp	5.41	18	4
	cosy	7.39	1	4		statue	5.17	17	6
	sleep	7.20	65	5		street	5.22	244	6
	warmth	7.41	28	6		table	5.22	198	5
	wise	7.52	36	4		taxi	5.00	16	4
Negative	bored	2.95	14	5	Maths	circle	5.30	60	6
	dreary	3.05	6	6		sphere	5.33	22	6
	sad	1.61	35	3		square	4.74	143	6
	gloom	1.88	14	5		pi	na	na	2
	dirt	4.17	43	4		arc	na	na	3
	mess	3.15	3	4		angle	na	na	5
	grime	3.37	1	5		maths	na	na	5
	pity	3.37	14	4		sine	na	na	4
	rusty	3.86	8	5		count	na	na	5
	weary	3.79	17	5		area	na	na	4

Table 4.1 Words used as primes in the affective priming task paired with an arithmetic verification task. Words could either have positive, negative or neutral valence, or be maths-related. Positive, negative and neutral words were selected from the ANEW (Bradley and Lang, 1999) while 7 maths-related words were selected outside of the database. Valence ratings and frequency of use are reported.

The stimuli in the verification task were arithmetic operations in the form a+b=c (table 4.2) belonging to all four operation types (addition, subtraction, multiplication, division). For each operation type, 8 simple and 8 complex operations were created. Simple operations consisted of single digit operands with the exception of two subtractions. Complex additions and subtractions consisted of double digit operands. For multiplications and divisions, half of them had both operands being double digits, while in half of them the first operand was a double digit and the second operand was a single digit. Each operand combination was paired with one correct and one incorrect solution. Incorrect solutions deviated ± 2 or ± 4 from the correct solution (Avancini et al., 2014). The following criteria were used for operands selection (Avancini et al., 2014): ties (e.g. 3+3) were excluded, 0 was not used as operand. Furthermore, every solution to the equations was a positive integer. Each operation was repeated twice in the experiment, for a total of 256 trials.

The trial (fig. 4.1A) started with the presentation of a fixation eye for 500ms followed by 500ms of blank screen. Then, the prime word was displayed for 250ms followed by the presentation of the operation. The operation was displayed until the subject made a response or for a maximum of 6 seconds. The intertrial interval was a 1,800ms blank screen. Participants were instructed to judge whether the operation was correct or incorrect and made a response by pressing keys on a keyboard with the right and left index fingers. Participants were encouraged to be as fast and as accurate as possible. The laterality of response buttons was counterbalanced across participants.

The experiment was composed of four blocks, each block belonging to one experimental condition determined by the emotional value of the prime. Therefore, in every block the prime words had the same emotional value. Each block consisted of the presentation of 64 trials. The words within each block and the operations across blocks were randomised. Furthermore, the block order was randomized across participants.

In order to elicit the startle reflex, 50ms bursts of white noise were presented binaurally at 102dB. In each block, the bursts were played at 12 randomly chosen intertrial intervals.

Only correct trails were retained for the statistical analysis. In addition, trials that received a response faster than 200ms were removed.

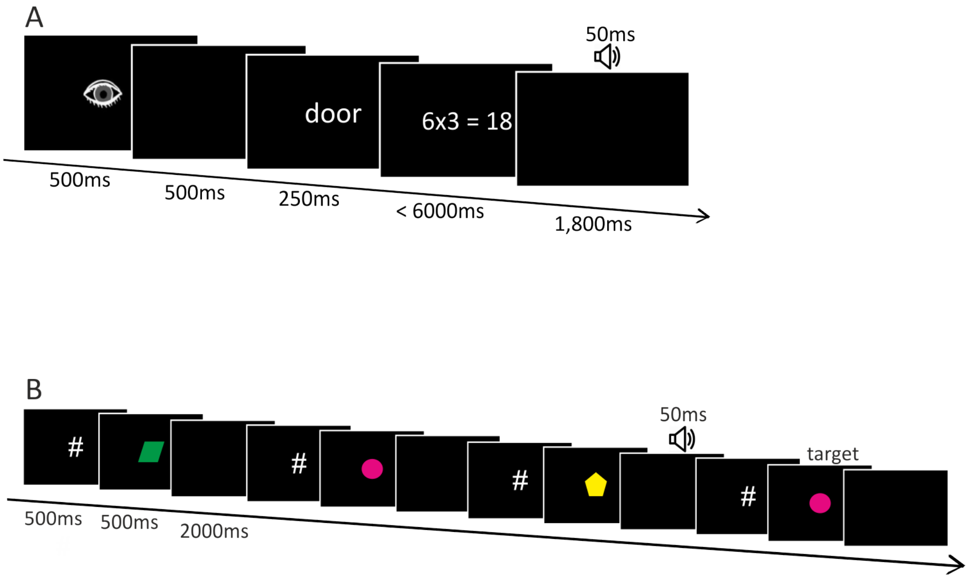


Figure 4.1 A) Example of trial in the affective priming task paired with an arithmetic verification task. Participants were presented with a priming word followed by an arithmetic operation. Participants were instructed to judge whether the operation was correct or incorrect. In 12 trials per block a 50ms burst of white noise was played to elicit the startle reflex. B) Example of trial in the two-back task. Participants were presented with coloured geometric shapes. The task required participants to give a response if the current stimulus was the same as the stimulus displayed two trials earlier. In 12 trials a 50ms burst of white noise was played. However, the startle reflex was not analysed for the two-back task as the purpose was to control for the influence of cognitive load on HRV in a task not involving emotion regulation.

Two-back task

In the two-back task stimuli appeared on black background and were displayed on a 17-inch Apple LCD monitor placed about 50 cm in front of the participants. Stimuli were coloured geometrical shapes centred at the centre of the screen. The trial (fig. 4.1B) started with a 500ms fixation "#". The fixation "#" was chosen over the eye because it was more easily distinguishable from the target stimuli. The fixation was followed by a stimulus displayed for 500ms and then by 2,000ms of blank screen. Participants were instructed to press a key when the stimulus displayed was the same of the stimulus displayed two trials earlier. Similarly to the verification task, 50ms bursts of white noise were presented binaurally at 102dB. In each block, the bursts were played at 12 randomly chosen blank intervals.

	Additions	Subtractions	Multiplications	Divisions
Simple				
Correct	6+7=13	16-7=9	4×9=36	6/2=3
	9+7=16	14-9=5	7×6=42	4/2=2
	5+9=14	9-6=3	3×4=12	8/2=4
	3+6=9	9-4=5	9×7=63	9/3=3
	5+4=9	8-5=3	6×3=18	6/3=2
	3+5=8	7-3=4	4×7=28	8/4=2
	4+3=7	11-3=8	8×6=48	7/1=7
	8+3=11	13-7=6	3×8=24	9/1=9
Incorrect	6+7=9	16-7=11	4×9=38	6/2=5
	9+7=18	14-9=7	7×6=44	4/2=4
	5+9=16	9-6=1	3×4=10	8/2=2
	3+6=7	9-4=3	9×7=61	9/3=1
	5+4=7	8-5=7	6×3=22	6/3=6
	3+5=12	7-3=8	4×7=32	8/4=6
	4+3=11	11-3=4	8×6=44	7/1=3
	8+3=7	13-7=2	3×8=20	9/1=5
Complex				
Correct	22+13=35	35-13=22	19×3=57	78/6=13
	11+17=28	28-17=11	6×14=84	84/6=14
	34+23=57	57-23=34	16×7=112	96/8=12
	16+43=59	59-43=16	4×17=68	68/4=17
	17+39=56	56-39=17	14×19=266	72/18=4
	47+26=73	73-26=47	15×13=195	78/13=6
	29+52=81	81-52=29	12×16=192	56/14=4
	64+19=83	83-19=64	18×17=306	96/16=6
Incorrect	22+13=37	35-13=24	19×3=59	78/6=15
	11+17=26	28-17=9	6×14=82	84/6=12
	34+23=61	57-23=38	16×7=116	96/8=16
	16+43=55	59-43=12	4×17=64	68/4=13
	17+39=58	56-39=19	14×19=268	72/18=6
	47+26=71	73-26=45	15×13=193	78/13=4
	29+52=85	81-52=33	12×16=196	56/14=8
	64+19=79	83-19=60	18×17=302	96/16=2

Table 4.2 Stimuli used in the affective priming task paired with a verification task. Operations were either additions, subtractions, multiplications or divisions. Half of the operations were simple and half complex. Simple operations had single digit operands or only one double digit operand in the case of subtractions. Complex operations had double digit operands or at least one double digit operand in the case of multiplication and divisions. In half of the trials the operations were correct and in half operations were incorrect.

4.2.4 Procedure

During recruitment participants were asked not to make use of tobacco or caffeinated drinks on the day of the testing. The reason was to reduce the effects of caffeine and nicotine on the physiological response to stress. On the day of the experiment, participants were asked to sign a consent form and fill in the personal details form prior starting the experiment. Half of the participants performed the verification task first, while half performed the two-back task first. The TAI (fig 4.8 in the appendix) and the STAI-trait (fig 4.10 in the appendix) questionnaires were administered online. Half of the participants were asked to complete them before coming to the testing session while half completed them after the testing session. The STAI-state (fig 4.9 in the appendix) was administered during the testing session. Half of the participants filled it before the computerized tasks and half after. In order to avoid that participants understood that the experiment was specifically about MA, the AMAS (fig 4.7 in the appendix) and the arithmetic difficulty questionnaire (fig 4.6 in the appendix) were always administered after the computerized task. The Reading Task (fig. 4.11 in the appendix) was administered at the end of the testing session.

After all electrodes were applied and before starting the recording, the participant was habituated to the startling noise with the presentation of 9 bursts of white noise. This procedure was employed to ensure that the strong startle habituation did not influence the results (Schmitz and Grillon, 2012). Then, the participant was asked to relax with the eyes closed for 5 minutes. This was to ensure that the HR was at resting state before the experiment begun. For the same reason, a 2 minutes rest in which the participant had to relax with the eyes closed was given in between experimental blocks.

4.2.5 Physiological data acquisition and processing

The ocular EMG signal and the ECG signal were recorded using the EOG100C and ECG100C BIOPAC system modules and the software AcqKnowledge (BIOPAC Systems, Inc., Santa Barbara, CA). The ocular EMG signal was acquired using three 4mm Ag/AgCl electrodes. The two active electrodes were placed below the lower eyelid 2cm apart and the ground electrode was placed on the forehead. The signal was sampled at 2000Hz with on-line 0.05Hz high-pass filter. The signal was then 40-500Hz band-pass filtered off-line in AcqKnowledge. The signal was segmented at -100ms to 2000ms relative to noise onset, rectified, baseline corrected (baseline -100ms to 0ms relative to noise onset) and averaged. For each condition, maximum peak amplitudes were identified. Statistical analyses were carried out on values obtained by the averaging the peak value and ± 2 datapoints around the peak. EMG segments in which the voltage did not peak over 0.01mV within the segment were removed. If for a participant 80% of the EMG segments could not be retained for all conditions, the participant was removed from the analysis. Furthermore, because of the high interindividual variability in startle response, startle data were converted into T-scores within participants. This allowed to establish a common metric across participants. T-scores were calculated by transforming z-scores: multiplying each z-score by 10 and then adding 50 (Levenston et al., 2000).

The ECG signal was acquired using three 11mm Ag/AgCl disposable electrodes. The Lead II configuration was chosen because it outputs large positive R peaks. In the Lead II configuration the positive lead is placed over the ribcage below the left breast, the negative lead is placed below the right clavicle and the ground lead is placed below the left clavicle. The signal was sampled at 2000Hz with on-line 0.05Hz high-pass filter. A 1Hz high-pass filter was applied off-line. The data was then visually inspected: noisy segments of the data were removed and the remaining good segments were concatenated. Peaks were identified as the R peaks of the QRS complex. IBIs were calculated as the time difference between consecutive R peaks. In order to exclude IBIs produced by ectopic beats, IBIs that were longer than 1,800ms and shorter than the 25% of the preceding IBI were removed. Because there is no consensus on the most appropriate way to edit ectopic beats (Lippman et al., 1994; Peltola, 2012), no interpolation was carried out. In the time domain, the HRV indices extracted were the mean of the IBIs from which ectopic beats have been removed, the SDNN and the RMSSD. In the frequency domain, the ratio of low frequencies to high frequencies (LF/HF) was calculated. In order to calculate the LF/HF, the spectral power was obtained with the Fast Fourier Transformation. The LF/HF was then obtained by computing the ratio between the integral of low-frequencies (LF boundaries: 0.04Hz-0.15Hz) and high-frequencies (HF boundaries: 0.15Hz-0.4Hz). Participants in which the signal was too noisy to detect R-R peaks, were removed from the analysis.

4.2.6 Statistical analyses

Participants were retained for statistical analysis only if they did not meet any exclusion criteria (see sections 4.2.2 and 4.2.5). The data of the mean of the IBIs and the SDNN were log-transformed to meet normality.

Hierarchical regressions were run to assess whether implicit measures predicted self-report scores at the AMAS. Regressions were run separately for each implicit measure. First, the regression coefficient of a regression with *Prime Type* as independent variable and *Implicit Measure* as dependent variable was calculated separately for each participant. Because the effect of prime on behavioural implicit measures was found to be inconsistent across studies and between genders (Rubinsten et al., 2012; Rubinsten and Tannock, 2010), the order of *Prime Type* as independent variable in the regression model was informed by the descriptive statistics of behavioural data (table 4.4). The prime order was the following: positive prime, negative prime, neutral prime, maths prime. The same order was kept for physiological data. Following individual regressions, a regression model with AMAS scores as predictor and individual regression coefficients (β) as response variable was run to assess whether implicit measures predictes AMAS scores.

The participants were sorted into LMA, MMA and HMA using the AMAS (Alexander and Martray, 1989). Participants falling within the first quartile were included in the LMA group, participants falling within the second and third quartiles were included in the MMA group and participants falling within the top quartile were included in the HMA group (Table 4.3). We obtained 12 LMAs, 16 MMAs and 12 HMAs. ANOVAs and BANOVAs with *Group* as between-subjects factor and *Prime Type* as within-subjects factor were run on all implicit measures. In the case of significant interaction in the overall ANOVA and support for the alternative hypothesis in the overall BANOVA, one-way repeated measure ANOVAs and BANOVAs were run to investigate the interaction. Pairwise t-tests Bonferroni corrected and pairwise bayesian t-tests were run to investigate contrasts between conditions.

Furthermore, because HRV is also sensitive to attentional processes (Börger et al., 1999; Luque-Casado et al., 2016; Richards and Casey, 1991), differences in HRV measures were investigated by means of pairwise t-tests Bonferroni corrected and bayesian t-tests between priming task, two-back task and resting state. Because the ANOVAs and BANOVAs on HRV data did not show any difference between conditions in the priming task (see section 4.3), the HRV data in the priming task were averaged across conditions to reduce the number of contrasts.

Anxiety level	**AMAS**	**TAI**	**STAI-state**	**STAI-trait**
LMA	11.33 $\overline{M}$	34.33 $\overline{M}$	29.67 $\overline{M}$	36.41 $\overline{M}$
	1.56 SD	12.91 SD	8.81 SD	8.96 SD
MMA	15.63 $\overline{M}$	38.00 $\overline{M}$	31.37 $\overline{M}$	36.56 $\overline{M}$
	1.15 SD	13.44 SD	7.59 SD	9.68 SD
HMA	22.75 $\overline{M}$	40.66 $\overline{M}$	34.58 $\overline{M}$	47.33 $\overline{M}$
	5.50 SD	13.09 SD	8.35 SD	8.79 SD

Table 4.3 Means ($\overline{M}$) and standard deviations (SD) of at the AMAS, TAI, STAI-state and STAI-trait questionnaires for the LMA, MMA and HMA groups.

4.3 Results

4.3.1 Complexity and operation type

As sanity check, we run a one-way ANOVA with Operation Type as factor and paired t-tests were run to check for the effect of Complexity on both reaction times (RTs) and accuracies.

For accuracies, the ANOVA run with Operation Type as factor was significant (F(3,117) = 43.45, p $\leq$ 0.001, η_p^2 = 0.27), result that was confirmed by the BF_{01} = 1.10e^{-28}. Pairwise t-tests Bonferroni corrected and bayesian pairwise t-tests showed that participants were more accurate on additions than subtractions (t(39) = 4.22, p $\leq$ 0.001, BF_{01} = 0.006), multiplications (t(30) = 9.91, p $\leq$ 0.001, BF_{01} = 3.75e^{-10}), and divisions (t(39) = 7.27, p $\leq$ 0.001, BF_{01} = 7.23e^{-7}). Furthermore, they were more accurate on subtractions than multiplications (t(39) = 7.24, p $\leq$ 0.001, BF_{01} = 7.78e^{-7}) and divisions (t(39) = 5.04, p $\leq$ 0.001, BF_{01} = 0.0005). For RTs, the ANOVA run with Operation Type as factor was significant (F(3,117) = 12.28, p $\leq$ 0.001, η_p^2 = 0.10), result that was confirmed by the BF_{01} = 4.19e^{-8} . Pairwise t-tests Bonferroni corrected and bayesian pairwise t-tests showed that participants were faster on additions than subtractions (t(39) = -8.78, p $\leq$ 0.001, BF_{01} = 8.88e^{-9}) and multiplications (t(39) = -4.22, p $\leq$ 0.001, BF_{01} = 0.006). Participants responded faster on trials with divisions than on trials with subtractions (t(39) = 3.60, p $\leq$ 0.01, BF_{01} = 0.03) and than on trials with multiplications (t(39) = 3.23, p $\leq$ 0.05). Regarding the contrast between subtractions and multiplications, however, a BF_{01} = 4.41 suggests that the data are likely to be observed under the null hypothesis. Descriptives are reported in table 4.5.

For Complexity, the pairwise t-tests and the bayesian pairwise t-tests showed that participants were more accurate (t(39) = 13.93, p $\leq$ 0.001, BF_{01} = 2.37e^{-34}) and faster (t(39) = -17.75, p $\leq$ 0.001, BF_{01} = 1.61e^{-64}) on simple compared to complex operations. Descriptives are reported in table 4.6.

4.3.2 Effect of anxiety

The ANOVA Anxiety Group $\times$ Prime Type was not significant neither for accuracy (F(6,111) = 1.27, p = 0.27) nor RTs (F(6,111) = 1.04, p = 0.41). A BF_{01} = 227.21 for accuracy and a BF_{01} = 56.37 showed that the data were respectively 227.21 and 56.37 times more likely to be observed under the null hypothesis. Finally, the main effect of Group was not significant neither for accuracy (F(2,37) = 1.15, p = 0.32, BF_{01} = 2.06) nor for RTs (F(2,37) = 0.08, p = 0.92, BF_{01} = 3.97).

The ANOVAs Anxiety Group $\times$ Prime Type (Fig. 4.3) were not significant and the BANOVAs suggested that the data were likely to be observed under the null hypothesis for startle data (F(6,111) = 1.39, p = 0.23, BF_{01} = 60.70), for the mean of the IBIs (F(6,111) = 1.06, p = 0.39, BF_{01} = 163.88), for the SDNN (F(6,111) = 1.90, p = 0.09, BF_{01} = 20.09) and LF/HF ratio (F(6,111) = 1.41, p = 0.22, BF_{01} = 14.94). For the RMSSD, the ANOVA Anxiety Group $\times$ Prime Type showed a significant main effect of Prime Type (F(3,111) = 3.57, p $\leq$ 0.05, η_p^2 = 0.09, BF_{01} = 0.67) and a significant interaction between the two factors (F(6,111) = 2.72, p $\leq$ 0.05, η_p^2 = 0.13, BF_{01} = 0.34). Pairwise t-tests Bonferroni corrected and bayesian t-tests showed that the difference between positive and negative primes was significant (t(39) = -2.75, p $\leq$ 0.05, BF_{01} = 0.22) with the RMSSD being higher for negative (μ = 63.44, σ = 44.53) than positive (μ = 57.97, σ = 39.40) primes. In order to study the interaction, three one-way ANOVAs and BANOVAs were run for each anxiety group with Prime Type as factor. The ANOVA and BANOVA run on MMA participants had an effect of Prime type (F(3,45) = 4.29, p $\leq$ 0.01, η_p^2 = 0.22, BF_{01} = 0.20). However, no pairwise comparisons Bonferroni corrected were significant. Finally, no effect of Prime Type emerged from the one-way ANOVAs and BANOVAs on LMA (F(3,33) = 0.12, p = 0.95, BF_{01} = 8.12) and on HMA (F(3,33) = 1.33, p = 0.28, BF_{01} = 2.74).

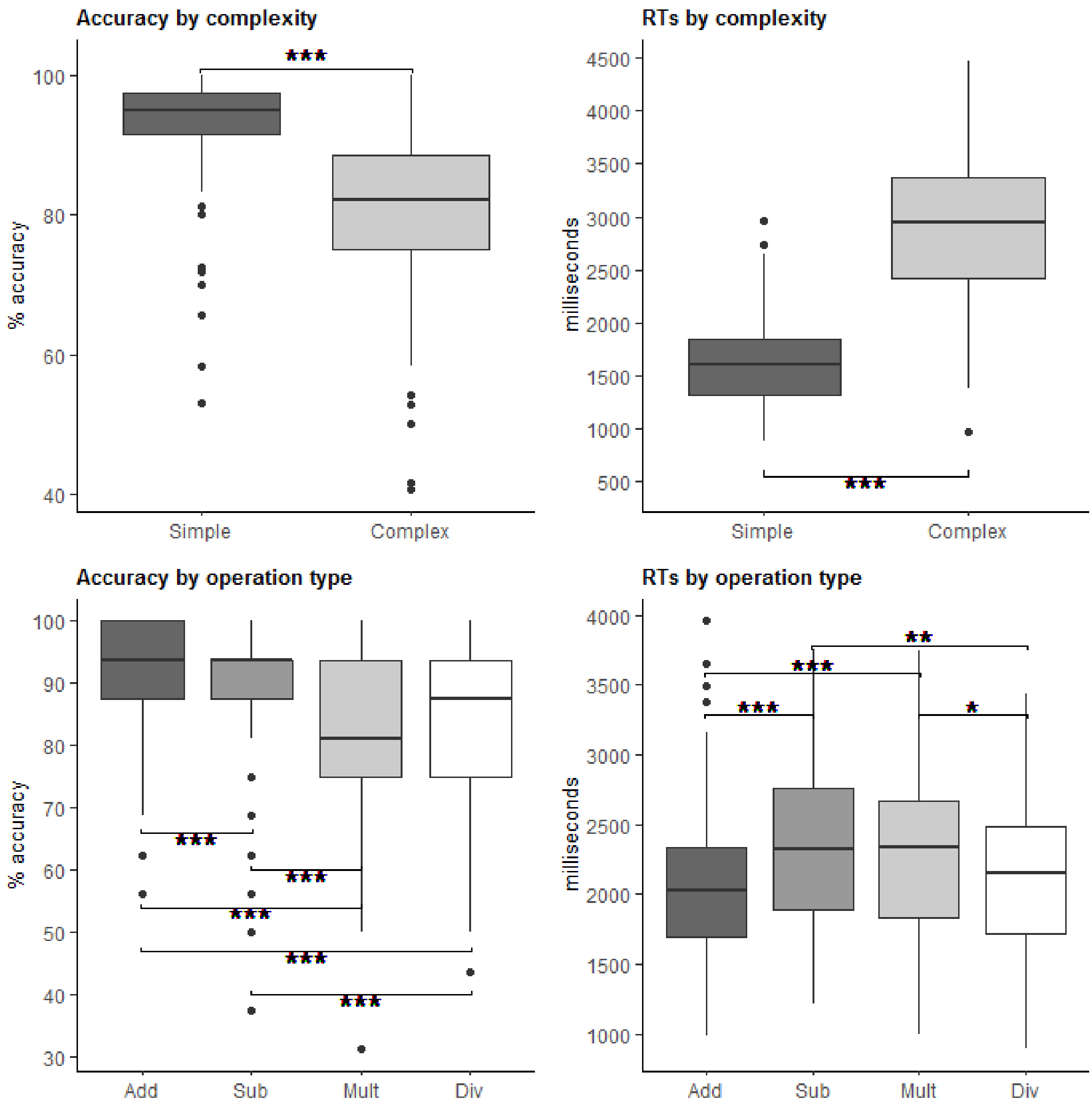


Figure 4.2 Boxplots of accuracy and RTs divided by complexity (top row) and operation type (bottom row). Significant contrasts are marked with asterisks: * p≤0.05, ** p≤0.01, *** p≤0.001.

	Positive	Negative	Neutral	Maths
Acc (%)	86.40 $\overline{M}$ 12.14 SD	86.40 $\overline{M}$ 11.94 SD	87.70 $\overline{M}$ 9.76 SD	88.71 $\overline{M}$ 10.28 SD
RTs (seconds)	2.18 $\overline{M}$ 0.83 SD	2.19 $\overline{M}$ 0.87 SD	2.31 $\overline{M}$ 0.87 SD	2.40 $\overline{M}$ 0.85 SD

Table 4.4 Means ($\overline{M}$) and standard deviations (SD) of accuracy and RTs for trials in the four affective priming conditions. Descriptives are calculated for all subjects grouped together.

	Additions	Subtractions	Multiplication	Divisions
Acc %	92.77 $\overline{M}$ 6.30 SD	89.81 $\overline{M}$ 7.79 SD	81.41 $\overline{M}$ 9.35 SD	83.95 $\overline{M}$ 8.78 SD
RTs (seconds)	2.07 $\overline{M}$ 0.45 SD	2.33 $\overline{M}$ 0.46 SD	2.29 $\overline{M}$ 0.45 SD	2.13 $\overline{M}$ 0.42 SD

Table 4.5 Means ($\overline{M}$) and standard deviations (SD) of accuracy and RTs for the four operation types. Descriptives are calculated for all subjects grouped together.

	Simple	Complex		Simple	Complex
Acc	93.52 $\overline{M}$ 6.43 SD	80.58 $\overline{M}$ 8.46 SD	RTs (seconds)	1.61 $\overline{M}$ 0.34 SD	2.90 $\overline{M}$ 0.59 SD

Table 4.6 Means ($\overline{M}$) and standard deviations (SD) of accuracy and RTs for simple and complex operations. Descriptives are calculated for all subjects grouped together.

4.3.3 Hierarchical regression

Following hierarchical regression on behavioural data, neither accuracy (F(1,38) = 0.01, p = 0.90, R^2 = 0.0004) nor RTs (F(1,38) = 0.56, p = 0.45, R^2 = 0.01) predicted scores at the AMAS (Fig. 4.4).

None of the physiological measures predicted AMAS scores (Fig. 4.4): neither startle amplitude (F(1,38) = 0.21, p = 0.65, R^2 = 0.005), nor the mean of IBIs (F(1,38) = 0.0001, p = 0.99, R^2 = 2.718e^{-6}), nor the SDNN (F(1,38) = 3.41, p = 0.07, R^2 = 0.08), nor the RMSSD

(F(1,38) = 0.17, $p = 0.89$, $R^2 = 0.0004$), nor the LF/HF ratio (F(1,38) = 0.05, $p = 0.83$, $R^2 = 0.001$).

4.3.4 Effect of WM load on physiological measures

Pairwise comparisons Bonferroni corrected and bayesian pairwise t-tests were run to assess the effect of task on HRV measures (Fig. 4.5). The mean of the IBIs was larger in the priming task than in the two-back task (t(39) = 2.68, $p \leq 0.05$, $BF_{01} = 0.26$) and than during the resting state (t(39) = 3.07, $p \leq 0.01$, $BF_{01} = 0.11$). The SDNN was larger in the priming task than in the two-back task (t(39) = 3.69, $p \leq 0.01$, $BF_{01} = 0.02$). The RMSSD was larger in the priming task than during the resting state (t(39) = 3.13, $p \leq 0.01$, $BF_{01} = 0.09$). Finally, the LF/HF ratio was smaller in the priming task then in the two-back task (t(39) = -3.86, $p \leq 0.01$, $BF_{01} = 0.26$). Descriptives are reported in table 4.7.

	Priming	**Two-back**	**Resting State**
means IBIs	6.72 $\overline{M}$ 0.14 SD	6.70 $\overline{M}$ 0.14 SD	6.70 $\overline{M}$ 0.16 SD
SDNN	4.19 $\overline{M}$ 0.45 SD	4.08 $\overline{M}$ 0.49 SD	4.11 $\overline{M}$ 0.53 SD
RMSSD	59.85 $\overline{M}$ 39.68 SD	55.04 $\overline{M}$ 38.18 SD	53.04 $\overline{M}$ 38.53 SD
LF/HF	2.91 $\overline{M}$ 0.50 SD	3.22 $\overline{M}$ 0.57 SD	3.09 $\overline{M}$ 0.77 SD

Table 4.7 Means ($\overline{M}$) and standard deviations (SD) of HRV measures in the priming task, two-back task and resting state. Because no difference between conditions was found in the priming task, data were grouped together.

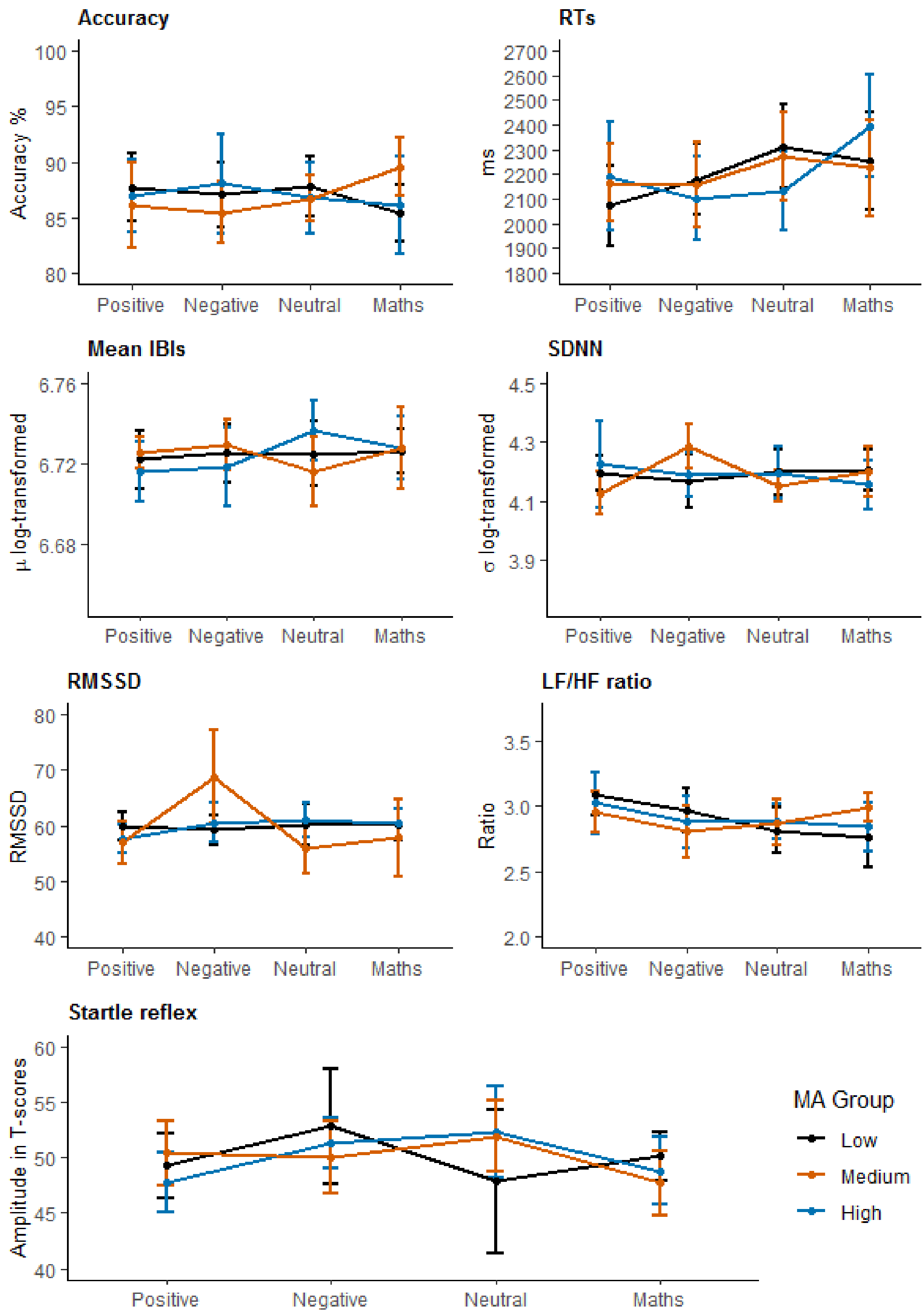


Figure 4.3 Plots of all implicit measures in the different affective priming conditions: accuracy, reaction times (RTs), mean of the interbeat intervals (IBIs), standard deviation of the NN intervals (SDNN), root mean square of the successive differences (RMSSD), ratio between low and high frequencies (LF/HF ratio) and the startle reflex. The coloured lines represent the three MA groups. Vertical lines are 95% confidence intervals. No interaction between Group and Prime Type was found to be significant in any of the implicit measures.

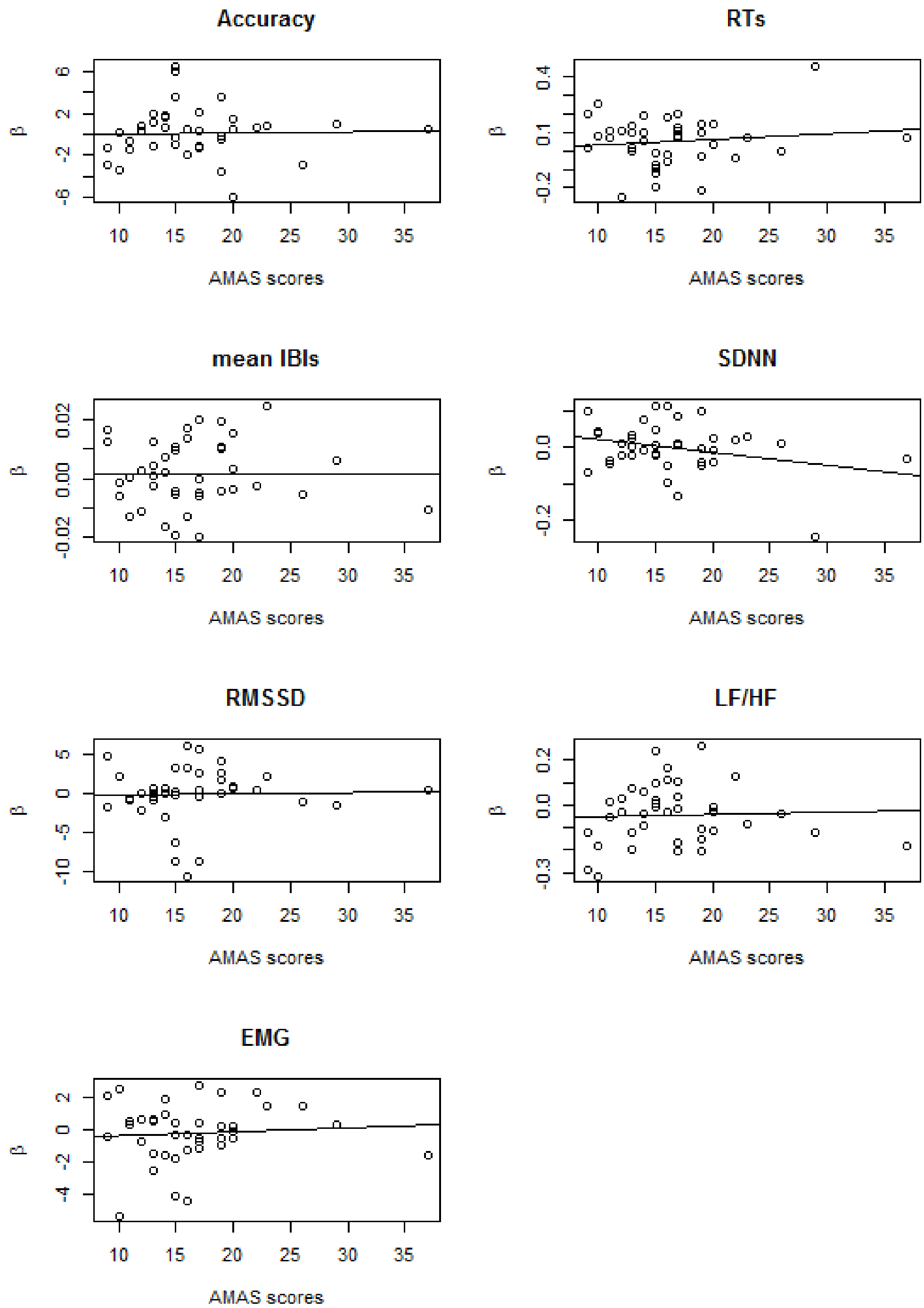
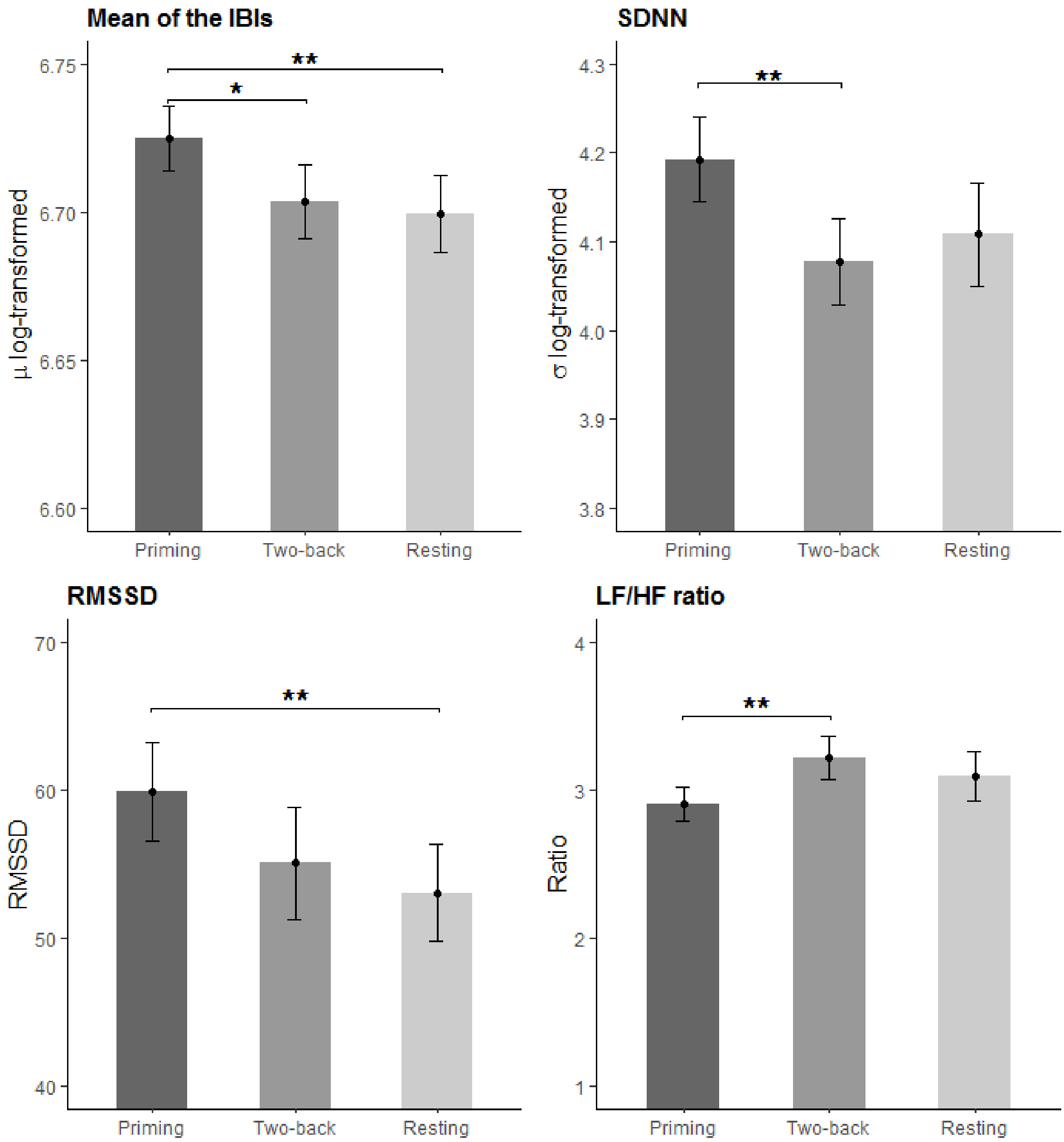


Figure 4.4 Fit of the regression models for the group data for each implicit measure: accuracy, reaction times (RTs), mean of the interbeat intervals (IBIs), standard deviation of the NN intervals (SDNN), root mean square of the successive differences (RMSSD), ratio between low and high frequencies (LF/HF ratio) and the startle reflex (EMG). On the x axis are AMAS scores as predictor. On the y axis are the β coefficients obtained at the individual level. The individual β coefficients were calculated for each participant by regressing the physiological measure values on the Operation Type variable. Levels of the Operation Type variable were ordered according to the behavioural descriptives.



Contrasts between tasks for HRV measures: mean of the interbeat intervals (IBIs), standard deviation of the NN intervals (SDNN), root mean square of the successive differences (RMSSD), ratio between low and high frequencies (LF/HF ratio). Because no difference between conditions was found in the affective priming task, data from the affective priming task were grouped together. Vertical bars represent 95% confidence intervals. Significant contrasts are marked with asterisks: * p≤0.05, ** p≤0.01, *** p≤0.001.

Figure 4.5 n

4.4 Discussion

The relationship between MA and maths performance is a question that is still under investigation. While some hypothesize that cognitive difficulties are the cause of MA, others suggest that MA interferes with executive functions such as WM and attentional processes, leading to poor maths performance (Carey et al., 2016). The difficulty in unravelling such complex relationship also depends on the complexity of MA in itself. MA is a complex construct that touches aspects of cognition, metacognition and physiology, making it challenging to measure and assess. The most common measure of MA is done through self report measures. However, self reports present two major limitations. First, their validity partially relies on honesty and metacognitive skills. Second, because of their narrative fashion they do not provide information on automatised processes affected by MA. Hence, the last two decades have seen an increased interest in implicit measures of MA.

In the present study, an affective priming task paired with an arithmetic verification task while measuring startle reflex and HRV was used to investigate implicit measures of MA. In the priming task, primes were words that could either have positive, negative or neutral valence, or be maths-related. Each prime word was followed by an arithmetic operation that the subject had to judge correct or incorrect. During the task, startle reflex and heart rate (to obtain HRV indices) were measured. Behavioural data and physiological data were analysed as implicit measures of MA. Differences in the affective priming effect between MA groups was assessed for both behavioural and physiological data. Furthermore, I looked at whether the AMAS predicted implicit measures values. Finally, to look at the influence that WM might have played on HR data, HRV measures during a two-back task and 5 minutes resting state were compared to experimental data from the affective priming task. Overall, the results obtained from this experiment did not allow me to reject the null hypothesis. Specifically, the emotional manipulation did not produce any effect on the implicit measures that could discriminate between different levels of MA. Similarly, implicit measures did not predict ratings to the AMAS scale. The comparison of physiological measures between the priming task and the two-back task suggests that there might have been a generic effect of emotional priming elicited by words carrying semantic meaning compared to simple WM load. However, such effect did not vary across anxiety group nor prime type.

4.4.1 MA and the affective priming effect on behavioural data

The effect of operation type and complexity on both accuracy and RTs confirms effects widely reported in mental arithmetic literature (Campbell and Alberts, 2009; Dagenbach and

McCloskey, 1992; De Smedt et al., 2010; Núñez-Peña et al., 2006; Roussel et al., 2002). A perhaps surprising effect is that divisions were solved faster than subtractions. However, the fact that responses to divisions were less accurate, suggests a speed-accuracy tradeoff. Although the main effect of Operation Type and Complexity did not contribute towards resolving the research question, it allows me to conclude that participants did understand the task and were performing it according to the task instructions. This is important especially in light of negative results obtained on factors interactions.

The results of the present experiment replicated neither the study of Rubinsten and Tannock (2010) nor Rubinsten et al. (2012). First, the BF_{01} of the Group $\times$ Prime Type interaction suggested decisive evidence for H_0 for accuracy and very strong evidence for H_0 for RTs (see section 4.3.2 and table 1.1 for BF interpretation). According to the previous work of Rubinsten and colleagues (2010, 2012), I expected HMAs to respond faster to operations when preceded by negative word primes compared to when preceded by positive word primes. That would have suggested that for HMAs the emotional valence of negative priming word acts as affectively related prime. Corroborating the suggestion that a priming task paired with an arithmetic verification task may be a tool to obtain implicit measures of MA. However, this was not the case in the present study. The main effect of MA group was not significant either and, while for accuracy there was only anecdotal evidence for H_0, there was substantial evidence for H_0 for RTs. Finally, the AMAS predicted neither accuracy nor RTs.

The present data suggest that MA did not affect performance on the verification task, regardless of Prime Type, that MA did not modulate priming effects and that AMAS scores do not predict behavioural data on the priming task. Taken together the results suggest that the affective priming task might not be an effective tool to measure MA.

4.4.2 Physiological data

The data suggested that the priming task did not have any effect on any of the physiological measures. Specifically, the evidence for H_0 was strong for the SDNN and for the LF/HF ratio, very strong for the startle reflex and decisive for the mean of the IBIs (see table 1.1 for BF interpretation). The RMSSD was the only HRV measure that showed an effect of Prime Type and a significant interaction. However, the evidence is not strong enough to allow me to interpret such a finding. First of all, decomposing the interaction did not reveal any significant pairwise comparison. Second, the BF_{01} of the main effect of Prime Type and of the interaction suggest that the evidence is only anecdotal. Finally, regarding the main effect of Prime Type, the BF_{01} for the pairwise comparison between positive and negative prime word types provides evidence neither for H_0 nor for H_1. Hence, no interpretation should be done on the RMSSD. Furthermore, AMAS scores did not predict any of the physiological measures.

HRV is not only sensitive to emotion regulation but also to attentional processes and cognitive workload (Börger et al., 1999; Luque-Casado et al., 2016; Richards and Casey, 1991). While all four priming conditions had comparable WM load as a result of stimulus randomization, the need of engaging attentional resources in itself might have overshadowed the effect of emotional priming. Therefore, I compared the HRV measures obtained during the priming task to a challenging WM task with no emotional manipulation and to a passive resting state. Regarding time measure of HRV, participants showed more variability in the priming task compared to the two-back task (in mean of the NN intervals and SDNN) and to the resting state (in the RMSSD). While no difference was found between priming conditions and while no difference was found between groups, higher HRV in the priming task compared to when no emotional regulation is required, might suggest that the affective priming task did induce emotion regulation in participants and that the variability was emotion-specific and not influenced by attentional processes. However, the data seem to suggest that the sensitivity of HRV measure to emotion regulation is not sensitive enough to discriminate between emotional valence or between MA group. Alternatively, the task did not induce any priming effect that could be detected by physiological measures. That would be supported by the lack of priming effect in the behavioural data.

Also frequency-domain measures distinguished the priming task from the two-back task. However, the directionality of the effect is unexpected. According to the classical interpretation of the LF/HF ratio, lower ratios are thought to reflect parasympathetic activation which is dominant when we engage in tend-and-befriend behaviours (Shaffer and Ginsberg, 2017). In the context of the present research, it seems unlikely that parasympathetic activation is the branch of the autonomic system mostly activated during a task involving maths. Especially in a sample in which HMAs were included, albeit the comparison between tasks was run on the whole sample. As reported in the introduction, HRV has been measured through a wide number of different indexes. In the present thesis and for sake of comprehensiveness both time-domain and frequency domain measures were included. However, it is known (as also reported in the introduction) that the interpretation of frequencies as measures of sympathovagal balance has been challenged (Billman, 2013; Shaffer and Ginsberg, 2017; Shaffer et al., 2014).

4.4.3 Limitations and directions for future research

The present study does not provide strong conclusions on implicit measures of MA. The failed replication of Rubinsten and Tannock (2010) and Rubinsten et al. (2012) on the level of behavioural data suggests that the lack of effect on physiological measures of MA might stem from the ineffectiveness of the task in itself. It could be argued that the frequentist ANOVAs with three groups were run on low power. Nevertheless, group sizes were comparable to those in Rubinsten and Tannock (2010) and Rubinsten et al. (2012). Furthermore, bayesian analyses strongly supported evidence for the null hypothesis. In addition, the regressions run on the whole group had poor fit and were not significant. It is possible that the ordering of the variable Prime Type in the individual regressions was not optimal. However, I chose such order informed by the descriptive statistics. No other order was used to comply with scientific rigour and prevent p-hacking.

One potential limitation concerns the level of anxiety of the sample. While the sample has been divided into three anxiety levels based on the distribution of AMAS scores within the sample, it may be that overall participants were not math anxious enough to display any physiological or behavioural effect at the emotional priming task. Indeed, Hopko et al. (2003a) report that in a sample of undergraduate students with mean age 19 the mean AMAS score was 21.1 (SD = 7.0) with reported gender differences (in females M = 21.9, SD = 6.9, in males M = 19.5, SD = 6.9). The majority of the sample in the current study is pooled from the population of university students at Cambridge. Given the high academic standard required to access such institution is notoriously high, it is possible that the sample was not adequately representative of the general population. With relatively low scores at the AMAS (table 4.2.2) the characteristics of the sample might have contributed at the lack of positive results.

Investigating the theoretical grounds of affective priming effects goes beyond the purpose of this study. Nevertheless, it may be hypothesized that the affective priming task influences behaviour by cognitively associating psychological events that hold similar emotional value. However, such effect may not be strong enough to elicit a full emotional response both behaviourally and physiologically. In the present study I adopted the task developed by Rubinsten and Tannock (2010) as it is one of the very few studies investigating behavioural implicit measures of MA and allowed me to build up evidence from the already limited literature available.

The fact that the manipulation did not elicit the expected results highlights the need of independent replication of the behavioural results. However, there are several aspects that may have contributed to a failed replication. The first factor may be the choice of priming words. The exact words used for the original study could not be used in this context as the original sample was formed of Hebrew speaking individuals while the present study was carried in an English speaking country. While the present selection of words attempted at keeping the same criterion (similar words length on average and similar valence score and same part of speech), other characteristics of the words might have played a role in the failed replication. For example, words were not matched for frequency. In particular, the database used for the selection of the English words (ANEW), did not contain enough maths words. As a result, the maths words used in this study were likely to be less common than those used by Rubinsten et al. (2012). Furthermore, other than language, cultural differences and differenced in educational practices should also be taken into consideration as possible covert variables influencing the failed replication.

Another difference concerns the group factor. In the current study, level of anxiety was the between-group factor. On the other hand, in Rubinsten et al. (2012) it was gender. The present study was designed on the assumption that the emotional priming effect could be regarded as valid and reliable measure of MA if it effectively distinguished between groups that are considered to differ in MA, regardless of the factor in itself. However, that is probably not the case in this scenario. One possibility is that the priming effect may be effective in assessing differences in MA between genders but not between anxiety levels. Considering that in Rubinsten et al. (2012) males and females presented somehow contrasting behavioural responses, grouping both genders together might have caused such effects to cancel out.

Finally, the present study suggests that it is yet too early to combine the assessment of behavioural and physiological implicit measures within one study. Given the need of replication and the methodological complexity of psychophysiological research, at this stage it is advisable to re-think how implicit measures of MA should be investigated. First, the number of psychophysiological indexes that may be employed in such research is quite big. A striking example is the number of measures of HRV, both in the time and in the frequency domain. While an abundant pool of measures may create an appealing ground for experimentation and testing, that comes with challenges. Indeed, a big number of measures may mean bigger variability in the results, especially at a stage in which literature on physiological measures of MA is scarce. That is particularly true in the context of physiology where there may be substantial individual variability and where the signal to noise ratio is admittedly an issue in the field. Hence, I believe that at this stage there should be an effort in employing a limited set of measures, aiming at narrowing down the pool to those that may be the most sensitive to assessing MA. In particular, it should not be overlooked that MA is a type of anxiety that affects real people in real life scenarios. Research should keep in mind the future goal of assessing MA in ecologically valid settings. Hence, not all measures may be suitable, for instance, during classroom testing. An example might be the startle reflex, which requires the presentation of white noise to be elicited. Hence, measuring the startle reflex might not be ideal for online testing during real-life scenarios. Another way in which research should be re-thought is by assessing implicit measures with the aid of experimental manipulations that have reliably elicited strong effects in MA individuals. Alternatively, by selecting a sample in which LMAs and HMAs present extreme scores to self-report measures. Indeed, a limitation of this study is that the priming effect might not have been efficient enough in eliciting an anxious response in MA individuals.

4.5 Conclusions

In summary, the aim of the present study was to investigate implicit measures of MA. The research question was driven by the existing gap between the available measures of MA mostly relying on self-report and the automatised nature of the processess affected by MA and of anxious responding. To this aim we used an affective priming task paired with an arithmetic verification task, as well as physiological recordings of the startle reflex and HRV. Despite the lack of sensitivity of the measures chosen in the present study to MA levels, the scientific interest on implicit measures of MA should not be abandoned but rather re-thought. First, replication of the available literature is paramount. Second, at this stage it is advisable to assess behavioural and physiological measures separately. Employing tasks that allow for a solid understanding of these measures before attempting to combine them in a comprehensive single paradigm should be the first step.

4.6 Declaration

Giada Roccabruna and Tinne Buelens contributed to the initial stages of the work presented in this chapter. In particular, they contributed to experiment designing and stimuli selection. Giulia Cristoforetti contributed to data collection. Finally, Dr Licoln J. Colling developed the MATLAB application used for heart beats detection and informed on statistical analyses.

4.7 Appendix

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The following page contains arithmetic problems. You have 2 min to solve as many equations as you can. Solve according to columns (A first, then B, then C, then D), and do no skip any of the equations.

Participant number 48 ______________ Date ___/___/2016

A	B	C	D
2 + 2 =	3 + 5 =	5 + 6 =	7 + 5 =
4 - 2 =	6 - 4 =	8 - 3 =	10 -3 =
2 x 3 =	3 x 5 =	6 x 7 =	8 x 4 =
4 : 2 =	9 : 3 =	32 : 8 =	27 : 3 =
2 + 3 =	3 + 6 =	6 + 6 =	8 + 9 =
5 - 2 =	7 - 4 =	9 - 8 =	10 - 2 =
2 x 4 =	3 x 6 =	6 x 8 =	8 x 9 =
6 : 2 =	12 : 3 =	36 : 6 =	72 : 9 =
2 + 4 =	4 + 4 =	6 + 7 =	9 + 6 =
5 - 4 =	7 - 5 =	9 - 5 =	10 - 6 =
2 x 5 =	4 x 5 =	6 x 9 =	9 x 7 =
8 : 2 =	12 : 6 =	42 : 7 =	48 : 6 =
2 + 5 =	4 + 5 =	6 + 8 =	9 + 5 =
5 - 3 =	8 - 5 =	9 - 7 =	10 - 5 =
3 x 3 =	5 x 6 =	7 x 4 =	9 x 9 =
10 : 2 =	15 : 5 =	18 : 3 =	42 : 7 =
3 + 4 =	5 + 5 =	7 + 4 =	9 + 7 =
6 - 2 =	8 - 6 =	9 - 6 =	10 - 7 =
3 x 4 =	6 x 6 =	7 x 7 =	8 x 8 =
6 : 3 =	24 : 4 =	64 : 8 =	21 : 3 =

Number of total answers ______________

Number of correct answers ______________

Number of incorrect answers ______________

Time (if all equations were solved before 2 min had passed) ______________

Figure 4.6 The arithmetic difficulties questionnaire (Openhaim-Bitton, 2003)

Participant number ____

Each of the following sentences will be read out to you. Please give each sentence a score in terms of how anxious you would feel during each situation. Use the scale at the right side and circle the number which you think best describes how you feel.

	Low anxiety	Some anxiety	Moderate anxiety	Quite a bit of anxiety	High anxiety
1. Having to use the tables in the back of a math book.	1	2	3	4	5
2. Thinking about an upcoming math test 1 day before.	1	2	3	4	5
3. Watching a teacher work an algebraic equation on the blackboard.	1	2	3	4	5
4. Taking an examination in a math course.	1	2	3	4	5
5. Being given a homework assignment of many difficult problems that is due the next class meeting.	1	2	3	4	5
6. Listening to a lecture in math class.	1	2	3	4	5
7. Listening to another student explain a math formula.	1	2	3	4	5
8. Being given a "pop" quiz in math class.	1	2	3	4	5
9. Starting a new chapter in a math book.	1	2	3	4	5

Figure 4.7 Items of the AMAS

Participant number ____

Directions

A number of statements which people have used to describe themselves are given below. Read each statement and then circle the appropriate number to the right of the statement to indicate how you *generally* feel:

1 = Almost Never, 2 = Sometimes, 3 = Often, 4 = Almost Always.

There are no wrong or right answers. Do not spend too much time on one statement but give the answer which seems to describe how you generally feel. Please answer every statement.

	ALMOST NEVER	SOMETIMES	OFTEN	ALMOST ALWAYS
1. I feel confident and relaxed while taking tests	1	2	3	4
2. While taking examinations I have an uneasy, upset feeling	1	2	3	4
3. Thinking about my grade in a course interferes with my work on tests	1	2	3	4
4. I freeze up on important exams	1	2	3	4
5. During exams I find myself thinking about whether I'll ever get through school	1	2	3	4
6. The harder I work at taking a test, the more confused I get	1	2	3	4
7. Thoughts of doing poorly interfere with my concentration on tests	1	2	3	4
8. I feel very jittery when taking an important test	1	2	3	4
9. Even when I'm well prepared for a test, I feel very nervous about it	1	2	3	4
10. I start feeling very uneasy just before getting a test paper back	1	2	3	4
11. During tests I feel very tense	1	2	3	4
12. I wish examinations did not bother me so much	1	2	3	4
13. During important tests I am so tense that my stomach gets upset	1	2	3	4
14. I seem to defeat myself while working on important tests	1	2	3	4
15. I feel very panicky when I take an important test	1	2	3	4
16. I worry a great deal before taking an important examination	1	2	3	4
17. During tests I find myself thinking about the consequences of failing	1	2	3	4
18. I feel my heart beating very fast during important tests	1	2	3	4
19. After an exam is over I try to stop worrying about it, but I can't	1	2	3	4
20. During examinations I get so nervous that I forget facts I really know	1	2	3	4

Figure 4.8 Items of the TAI

DIRECTIONS:

A number of statements which people have used to describe themselves are given below. Read each statement and then circle the appropriate number to the right of the statement to indicate how you feel *right* now, that is, *at this moment*. There are no right or wrong answers. Do not spend too much time on any one statement but give the answer which seems to describe your present feelings best.

	NOT AT ALL	SOMEWHAT	MODERATELY SO	VERY MUCH SO
1. I feel calm	1	2	3	4
2. I feel secure	1	2	3	4
3. I am tense	1	2	3	4
4. I feel strained	1	2	3	4
5. I feel at ease	1	2	3	4
6. I feel upset	1	2	3	4
7. I am presently worrying over possible misfortunes	1	2	3	4
8. I feel satisfied	1	2	3	4
9. I feel frightened	1	2	3	4
10. I feel comfortable	1	2	3	4
11. I feel self-confident	1	2	3	4
12. I feel nervous	1	2	3	4
13. I am jittery	1	2	3	4
14. I feel indecisive	1	2	3	4
15. I am relaxed	1	2	3	4
16. I feel content	1	2	3	4
17. I am worried	1	2	3	4
18. I feel confused	1	2	3	4
19. I feel steady	1	2	3	4
20. I feel pleasant	1	2	3	4

STAIP-AD Test Form Y
www.mindgarden.com

Figure 4.9 Items of the STAI-state

Participant number ____

DIRECTIONS

A number of statements which people have used to describe themselves are given below. Read each statement and then circle the appropriate number to the right of the statement to indicate how you *generally* feel. There are no right or wrong answers. Do not spend too much time on any one statement but give the answer which seems to describe how you generally feel.

	ALMOST NEVER	SOMETIMES	OFTEN	ALMOST ALWAYS
21. I feel pleasant	1	2	3	4
22. I feel nervous and restless	1	2	3	4
23. I feel satisfied with myself	1	2	3	4
24. I wish I could be as happy as others seem to be	1	2	3	4
25. I feel like a failure	1	2	3	4
26. I feel rested	1	2	3	4
27. I am "calm, cool, and collected"	1	2	3	4
28. I feel that difficulties are piling up so that I cannot overcome them	1	2	3	4
29. I worry too much over something that really doesn't matter	1	2	3	4
30. I am happy	1	2	3	4
31. I have disturbing thoughts	1	2	3	4
32. I lack self-confidence	1	2	3	4
33. I feel secure	1	2	3	4
34. I make decisions easily	1	2	3	4
35. I feel inadequate	1	2	3	4
36. I am content	1	2	3	4
37. Some unimportant thought runs through my mind and bothers me	1	2	3	4
38. I take disappointments so keenly that I can't put them out of my mind	1	2	3	4
39. I am a steady person	1	2	3	4
40. I get in a state of tension or turmoil as I think over my recent concerns and interests	1	2	3	4

STAIP-AD Test Form Y
www.mindgarden.com

Figure 4.10 Items of the STAI-trait

Word Reading *(continued)*

Participant number ____

Item	Response	'Live'	Score	>3"	SC
C 81. flexible			0 1		
82. known			0 1		
83. equal			0 1		
D 84. fraction			0 1		
85. design			0 1		
86. smudge			0 1		
87. oxygen			0 1		
88. column			0 1		
89. thumbnail			0 1		
90. rhythm			0 1		
91. courage			0 1		
92. determine			0 1		
E 93. ajar			0 1		
94. apology			0 1		
95. pier			0 1		
F 96. ruin			0 1		
97. dozing			0 1		
98. useless			0 1		
99. ideally			0 1		
100. deputy			0 1		
101. cutlery (kət´-la-rē)			0 1		
102. phonograph			0 1		
103. poise			0 1		
104. unique			0 1		
105. pathetic			0 1		
106. cleanse			0 1		

Item	Response	Score	>3"	SC
107. chord		0 1		
108. acquire		0 1		
109. scholar		0 1		
110. treacherous		0 1		
111. veterinary (ve´-tə-rə-ner´-ē)		0 1		
112. ridicule		0 1		
113. vicinity		0 1		
114. negotiate		0 1		
115. catastrophe		0 1		
116. infamous (in´-fə-məs)		0 1		
117. topography (tə-pä´-grə-fē)		0 1		
118. naive (nä-ēv´)		0 1		
119. subtle (sut´-'l)		0 1		
120. bureau (byoor´-ō)		0 1		
121. plethora (ple´-thə-rə)		0 1		
122. reminisce (re-mə-nis´)		0 1		
123. conscience		0 1		
124. indefatigable		0 1		
125. malign (mə-līn´)		0 1		
126. indigenous (in-di´-jə-nəs)		0 1		
127. euphemism (yü´-fə-mi´-zəm)		0 1		
128. milieu (mēl-yə´ or mel-yoo´)		0 1		
129. antithesis (an-ti´-thə-səs)		0 1		
130. ethereal (i-thir´-ē-əl)		0 1		
131. hierarchical (hī-(ə-)´rär-ki-kəl)		0 1		

Total >3" Tick Marks

Total SC Tick Marks

RAW SCORE (max = 131)

Word Reading Qualitative Observations

Note how frequently a behaviour occurred by ticking the appropriate box.

	Never	Seldom	Often	Always	Not Observed
Substitutes a visually similar letter when identifying letters	☐	☐	☐	☐	☐
Provides nonword responses for rhyming words	☐	☐	☐	☐	☐
Pronounces words automatically	☐	☐	☐	☐	☐
Laboriously "sounds out" words	☐	☐	☐	☐	☐
Self-corrects errors	☐	☐	☐	☐	☐
Loses his/her place when reading words	☐	☐	☐	☐	☐
Makes accent errors	☐	☐	☐	☐	☐
Adds, omits, or transposes syllables when reading words	☐	☐	☐	☐	☐

Figure 4.11 Items of the Word Reading task

4.8 References

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Chapter 5

General Discussion and Conclusions

5.1 Theoretical framework

The present research project adopted physiological measures to investigate the relationship between anxiety and working memory (WM). I decided to employ physiological measures because they are sensitive to both anxious responses and executive processes. Given the importance of WM for maths processing, physiological measures are appealing for advancing our understanding of maths anxiety (MA).

WM is a limited capacity system where information is temporarily maintained and manipulated in order to perform a task (Baddeley, 2010). The understanding of WM has drawn substantial interest in the area of cognitive psychology and neuroscience since the first conceptualization of a short term storage (STS) by Atkinson and Shiffrin (1971). Since then, several models of WM have been developed. The model of Baddeley (Baddeley, 1992) has had great influence on how we understand WM to this date. The main contribution of Baddeley is the identification of distinct WM susbsystems that carry out specialized functions. Of particular interest for the theoretical framework of this thesis is the central executive. The central executive, as intended by Baddeley, is a modality-free subsystem that exerts attentional control over encoded memory representations.

There are several reasons why the concept of central executive has influenced the current work. First, executive functions are tightly related and partially overlap with attention. Furthermore, attention plays a central role in both encoding and maintenance of information in WM. Second, attentional and executive control are thought to be processes affected by anxiety and to explain poor performance to cognitive tasks in anxious individuals. Third, I believe that the intertwined relationship between attentional control, anxiety and performance is key to understanding MA.

5.2 Experimental work

The overarching question of the present thesis was whether anxiety affects the accuracy of the representations in WM and whether that explains the detrimental effects of MA on performance. WM is a process that is thought to be central to performing maths tasks and hence it may have a key function in explaining the relationship between maths performance and MA. Furthermore, this work approached the construct of anxiety from two angles. First, in terms of source of noise causing a decrease in performance to tasks relying on WM. Second, as evolutionary determined physiological reaction to stressors. The former conceptualization of anxiety informed the parts of this thesis investigating the effects of anxiety over WM. The latter provided the starting point to investigate how physiological measures may provide insights on the relationship between WM processes and maths performance. Thus, overcoming the limitations of self-report measures by taking advantage of the automaticity of physiological responses. The work was carried out through three experiments that will be now discussed.

The first experiment that was carried out (chapter 2) looked at attentional processes engaged prior to memory encoding. While no anxiety was directly investigated, the idea behind the experiment was to capitalize on the prestimulus subsequent memory effect (psSME) originally reported by Otten et al. (2006). The aim was to assess whether the psSME could be a phenomenon that may later be analysed to provide a insight on how anxiety effects WM even before a stimulus is presented. Indeed, a central cognitive characteristic of anxiety is the anticipation of threat. In more detail, selective attention as well as vigilance are thought to be mechanisms through which items gain access to WM (Gazzaley and Nobre, 2012). The psSME was first observed by Otten et al. (2006) and refers to the phenomenon for which prestimulus ERPs predict whether an item will or will not be encoded in memory. While Otten et al. (2006) suggested that the psSME reflects semantic encoding, I argued that it may instead reflect attentional processes. The interest in disambiguating the nature of the psSME is to be linked to the influence of anxiety on WM. Indeed, anticipation of threat is a key feature of anxiety (Grillon, 2008). If the psSME reflected attention allocation before the presentation of a stimulus, it would provide a useful tool to investigate how anxiety might affect the efficiency of WM memory encoding even before a stimulus is presented. Hence, the rationale behind the choice of investigating the psSME in the context of anxiety was driven by the common anticipatory aspect of both attention and anxious responding.

To test whether the ERP psSME reflects attentional processes, I first wanted to replicate Otten et al. (2006)'s work. Indeed, how reviewed in chapter 2 introduction, the topography and timing of the psSMEs reported in literature vary substantially. To this aim, I recruited 60 participants (Otten et al. (2006) only tested 24 participants and run analysis on 21) to achieve better statistical power. As part of the experiment, participants had to perform the same encoding and recalling tasks as in the original paper. Then, to test if the psSME reported by Otten et al. (2006) is determined by attention mechanisms, the same sample of participants was asked to perform an attention task. The attention task was a novel paradigm that I developed specifically to make prestimulus ERPs comparable between tasks. The stimuli in the attention task were strings of letters so no semantic process could be used to perform the task. Second, the trials belonged to two conditions (*high-attention* and *low-attention*) that depended on whether the preparatory engagement of attentional resources was key in order to perform the task. The rationale was that the *high-attention* and *low-attention* conditions corresponded to the *remembered* and *forgotten* conditions of the encoding task, if the processes involved were the same.

As reported in the results section of chapter 2, we replicated Otten's psSME in the encoding task. However, I decided to analyse the data of the present thesis with both frequentist and bayesian statistics. While the effect was reported as significant by frequentist analysis, the BF obtained suggested that the evidence was inconclusive. Furthermore, no evidence for an attentional effect was found in the attention task. Although from a first look at the data it seemed that the direction of the ERP polarity were consistent with the hypotheses, the effect did not reach significance. A lack of effect in the attention task invalidated any conclusion I could draw from the difference, or lack thereof, between the two tasks.

During data preprocessing, I encountered challenges in correcting for eye-blinks due to the length of the analysed epochs. Several algorithms are available for eye-blinks correction, however I wanted to approach the present research project with rigour and I wanted to give preference to conservative methodologies. As a result, the data suffered a consistent reduction. At the level of subject number (39 out of 60 were retained for analyses) and at the level of trials per condition. Therefore, a combination of reduced power, high signal variability and the psSME effect size made the present data only partially informative on psSMEs.

Criticism may also be directed to the choice of tasks. First, one might argue that the paradigm proposed by (Otten et al., 2006) tests encoding in long term memory (LTM). However, I believe that this does not invalidate the choice of the encoding task. As reviewed in the introduction, it is believed that retention of information in WM is a precursor of encoding in LTM. As already early models suggested (Atkinson and Shiffrin, 1971), executive processes in WM have, amongst others, the function of preventing the decay of memory representations. Maintained representations are then thought to be fed into LTM. Hence, I do believe that the choice of task is still relevant in relation to the overall scope of this thesis. Second, one might argue that the choice of the attentional task was suboptimal given that it was not a well established task. On one hand I would agree with such concern. On the other, no other attention task in literature were suited to assess the psSME when considering comparing the data with prestimulus ERPs from the encoding task. Moreover, the novelty of the task wanted to be a contribution to original research despite risks of negative findings.

The results from the first experiment suggested that the psSME may indeed reflect semantic processes rather than the recruitment of attentional resources. However, the results are not unequivocally conclusive because of the methodological issues that contributed to a signal to noise ratio that was below being ideal. If the psSME was indeed determined by attentive processes, how induced anxiety affected such recruitment and how that affected encoding in WM would have been the logical further questions to be asked. That would have then led to the assessment of how anxiety affects memory representations during maintenance, as done in the second experiment (chapter 3). It could be argued that the task adopted to assess the psSME actually investigated LTM processes on verbal material while the following aim was to look at the effect of anxiety on VSWM, which is the function thought to be central to maths processing. The choice of task was made because the effects that were originally reported were assessed using words. My prediction was indeed that such effects were not a result of the recruitment of semantic processes but rather of attentional resources irrespective of any semantic information carried by the stimulus. The experiment aimed at providing a disambiguation between these processes, predicting that attentional processes explained the psSME, which would have provided a starting point for addressing how anxiety affects encoding in memory. That would have been particularly relevant in light of the overlapping concepts of attention an WM in resource models, upon which the data of chapter 3 were modelled. Nevertheless, the results to the first experiment did not justify further investigation of the psSME in the context of the influence of anxiety over WM processes.

A mentioned, attention was central to the work carried out in chapter 3. In particular, attentional processes are intended as functional to the maintenance of representations in WM, specifically in visuospatial WM. As reviewed in this thesis' introduction, resource models of WM theorizes that WM is a limited resource system (Bays et al., 2009). These resources are indeed attentive and are flexibly allocated. As a result, they can be redistributed across the entire pool of items or can redirected, even retrospectively, towards task-relevant items at cost of other items' representations. Furthermore, representations in WM carry a certain degree of noise. As a result, precision of recall may vary as function of several factors such as set size or the salience of specific items for task performance (Bays et al., 2009). The chapter aimed at directly answering the question of whether anxiety affects the maintenance of items in VSWM. I hypothesized that anxiety might impact the ability of attentional resources to deal with noise, resulting in decreased precision of recall.

To test the hypothesis I combined a delayed-recall task with the NPU-threat of shock protocol. This protocol is a well established technique to experimentally induce anxiety (Schmitz and Grillon, 2012). It has been developed on the assumption that anxiety is elicited by the anticipation of unpredictable threatening stimuli. Anxiety was measured using the startle reflex. The experimental manipulation successfully elicited anxiety as shown by startle data. However, there was no difference in precision of recall between the conditions. As thoroughly elaborated in chapter 3 discussion, the lack of anxiety effect on precision of recall might be due to several factors. One possibility is that anxiety does not decrease the ability of executive functions to deal with noise. A second possibility is that set size was too small for anxiety to have an impact on attentional resources detectable in behavioural data. Third, the choice of shock delivery time within the trial might not have been ideal.

In the context of the overarching question of the present thesis, the chapter was aiming at providing an insight on whether the detrimental effects of anxiety on maths performance was due to increased noise in VSWM that would result in reduced discrimination between memory representations. This would have suggested a mechanism through which MA affected maths performance. The lack of effect may be due to the resilience of VSWM to noise or specific methodological choices such as set size and type of threat. If the resilience of VSWM explained the outcome of the study, then the processes affected by MA may be ascribed to the verbal rather than visuospatial subsystem if WM. Alternatively, it may simply be resilient up to a certain level of memory load that was not reached in the present experiment. On the other hand, if the choice of threat is what has driven the results, that highlights the necessity of adopting paradigms that are ecologically valid. That would be particularly true in the context of MA in which the anxious response and its resulting physiological arousal are elicited by a very specific kind of threat such as maths.

Despite the null results, chapter 3 still provides some advancements in the field. On the technical level, it suggested how threat of shock and delayed-estimation paradigms could be used to investigate how anxiety effects memory. Second, it suggests (although it should be replicated) that with small set sizes attentional resources are sufficiently resistant to anxiety and able to deal with noise. Because of the null results, several adjustments could have been done to the study. For example, the same study could have been run with a higher number of trials in order to rule out that the results where due to the resilience of VSWM to anxiety at a relatively low memory load. It could be argued that dropping such choice constitutes a missed opportunity. While agreeing, I would also argument that the thesis proposed investigate the effect of anxiety in the framework of MA. Unfortunately, the specific question on the impairment of WM under the influence anxiety could not be conclusively addressed and further investigation would have deviated the focus of the thesis towards a narrow investigation on WM. While that would have been interesting and justifiable in it's own rights, the original idea was to assess the effect of anxiety on basic cognitive processes in order to shed light on the mechanisms impacted by MA. Because such link could not be established, we made the methodological choice to look at anxiety from the perspective of a physiological reaction to threat. This may have allowed us to take advantage of the automaticity of physiological arousal to study MA, overcoming limitations of subjective reporting. Hence, the choice was made to focus on MA in terms of an automatic physiological response induced by a the cognitive association between maths and threat.

The experimental work carried out in chapter 4 looked at physiological measures of MA. The link between maths processing and WM is widely accepted and it was reviewed in the introduction of this thesis. In particular, studies consistently found evidence for the involvement of the central executive in performing maths while the involvement of the slave systems seems less clear (DeStefano and LeFevre, 2004). MA is usually measured by means of self report questionnaires (Devine et al., 2012). The use of self-reports, although widespread and easy to implement, has its limitations. Questionnaires assume honesty in the responses, good metacognition and a certain degree of linguistic and cultural homogeneity. All factors that make questionnaires easily affected by biases. Most importantly for the present thesis, physiological change is a core aspect of anxious responding. Moreover, WM has been found to mediate the relationship between MA and physiological measures in several instances (Al'Absi et al., 2002; Shaffer and Ginsberg, 2017; Vedhara et al., 2000). Taken these factors together, investigating physiological arousal is necessary to reach comprehensive understanding of MA.

The aim of chapter 4 was to assess physiological measures in MA while replicating Rubinsten et al. (2012)'s results. In Rubinsten et al. (2012), the task is an affective priming task paired with an arithmetic verification task. Such task was developed by to assess implicit behavioural responding in MA participants. Affective priming words were presented before an arithmetic operation that participants had to judge correct or incorrect. Startle reflex and HRV indices were analysed as physiological measures. Furthermore, participants performed an 2-back task to assess the influence of WM on HRV indices as opposed to HRV emotional regulation. Data were analysed for three MA groups and implicit measures were compared to AMAS scores.

I was not able to replicate the original findings on behavioural measures. I could not detect differences related to levels of MA neither in behavioural measures nor in physiological measures. Given that I could not detect a group difference, it is not surprising that no difference was detected in the physiological indices as well. Regarding WM, HRV indices seemed to suggest that HRV reflected some emotional regulation happening during the affective priming task. However, given that no group effect was found, little can be drawn in terms of anxious responding in the context of MA.

The study wanted to combine the replication of previous literature that provided a first attempt at using implicit measures of MA (Rubinsten and Tannock, 2010) with the assessment of physiological indexes as potential implicit measures. Language differences between the original study (conducted in Hebrew) and the present study (conducted in English) constituted the main methodological challenge. That is because the priming words had to be drawn from different databases. On one hand, it may be argued that cognitive and physiological effects should be robust enough to overcome language differences. That is true especially if looking at the bigger picture, where research in cognitive and educational contexts should be able to provide knowledge that is applicable to real life scenarios, in which the complexity of the reality requires methodologies to be robust to the influence of covert variables. On the other hand, research should start from basic questions and provide incremental knowledge from the available literature. Combining ecologically valid research and a suitable experimental paradigm has been proved to be a challenging task.

5.3 A note on failed replication

The present work did not output the results that every researcher would hope for the sake of academic publications and, why not, personal satisfaction. Did this project fall into the quicksand of the replication crisis? The studies in this thesis present some limitations that have been reported in the experimental chapters. However, I believe discussing issues related to failed replication is relevant for integrating the results of the present thesis within the bigger picture of scientific research.

In a multi-year study, Johnson et al. (2017) attempted to replicate 100 psychological experiments. 97% of the original studies reported significant results but only 36% of the replicated ones did. The authors suggest that more than 90% of tests performed in psychology tested negligible effects. Furthermore, Szűcs and Ioannidis (2017) analysed published effect sizes and statistical power in influential psychology and cognitive neuroscience journals. Shockingly, journal impact factor negatively correlated with statistical power. The authors concluded that false report probability may exceed 50% for the literature in the field.

There are several factors that can undermine reproducibility. Low power, analyses flexibility, selective reporting, unclear methodology are all factors that increase the probability of Type I error as well as inflating true effect sizes (Button et al., 2013; Ioannidis, 2008).

It has been reported that it is not uncommon practice to repeatedly check for statistical significancy while gradually adding participants and to post-hoc regroup participants by unplanned grouping variables (Szűcs, 2016). Moreover, researchers often treat p-values as a trichotomous index for *strong evidence*, *weak evidence* and *no evidence* while in fact p-values is a continuous variable (Gelman, 2013). Finally, in neuroscience procedures of double-dipping are widespread (Kriegeskorte et al., 2009). All together, improper practices and misconception of frequentist statistics contribute to low replicability in the field. By raising the issue of reproducibility I am not necessarily pointing the finger against the specific work upon which this thesis has been developed. However, I do think that it is important to be aware that methodological pitfalls are common and at times accepted in our field.

The experiment reported in chapter 2 attempted a direct the replication of the psSMEs reported in the study of Otten et al. (2006). To do so the same experimental procedure was used, keeping stimuli and presentation the same. There were two main differences between the two studies. As mentioned in the chapter, the list of words were matched for word length and for occurrences per million although not all words were the same between the two studies. That is because I thought that some words included in the original paper were ambiguous when it came to animacy judgement (as it was the case for words of fruits and vegetables). Having substitute those with non-ambiguous words, should have not impacted the results. A second difference concerns the recording equipment and some data preprocessing choices. While Otten et al. (2006)'s data were recorded with 58 scalp electrodes, the data in the present thesis were recorded with 129 electrodes. Furthermore, some preprocessing choices differed. For example, in the original paper eye-blinks were corrected with regression methods while in this thesis epochs with eye-blinks were rejected. In both studies data were analysed on a minimum of 15 good trials per condition. Other details on the preprocessing, for example the maximum number of interpolated channels accepted for analysis were not reported by Otten et al. (2006). Unfortunately, it is unrealistic to expect that all studies are run with the same equipment and preprocessing choices are also made on the basis of the quality of the collected data, which is liked to the quality of the recording system and setup. It is possible that the fact that producing a weak and non-conclusive replication of the psSME while having better statistical power (n=39 in the present research while n=21 in the original paper) was influenced by the quality of the data and by preprocessing choices. That is the reason why published preprocessing pipelines like the PREP-pipeline (Bigdely-Shamlo et al., 2015) used in chapter 2 should be encouraged.

Regarding chapter 3, the results do not necessarily constitute a failed replication. That is because the independent variable was different from the ones of the original papers (Bays et al., 2011; Pertzov et al., 2013). In the original studies stimulus features such as number of items or type of presentation were the independent variables manipulated. However, in the experiment reported in chapter 3, the experimental manipulation was probability of shock which was unrelated to the stimuli. Because the manipulation of the independent variable was of different in nature between the two studies, null results reflect a genuine absence of effect rather than a failed replication.

There are three points that should be discussed regarding the null results of chapter 4. The first is that some of the dependent variables chosen were different from the original studies upon which the experiment was designed (Rubinsten et al., 2012; Rubinsten and Tannock, 2010). Not only, while heart rate had already been used to assess MA (Hopko et al., 2005, 2003), the experiment in chapter 3 was the first attempt at analysing indexes of heart rate variability (HRV). Hence, the results on behavioural implicit measures found in (Rubinsten et al., 2012) could not be replicated, or rather, could not be generalised to other implicit measures.

The second aspect concerns the fact that the effect over behavioural data was not replicated. Such failed replication may be due to a missed generalisation of the effect to a sample that has been grouped according to different criteria. While in the original study the group factor was gender, in the present research the group factor depended on anxiety levels. The assumption made when designing the experiment was that, if the effective priming task was a valid measure of MA, then the effect found between genders should also be found between levels of anxiety given comparable demographics between the studies. In the discussion of chapter 4, a point was raised about how the differences in AMAS scores between groups were small probably due to the high achieving university population. However, my argument is that replication becomes difficult when effects are not robust enough to be generalised to different groups under the same assumption. In this specific case, that the groups differ in the subjective response to maths-related stimuli. Publication of both positive and null results, as well as all effect sizes would greatly help in interpreting results and in informing better experimental designs.

Finally, the third aspect concerns the difficulties in replicating results across different languages when the task requires verbal stimuli or a verbal response. The issue with replicating Rubinsten et al. (2012)'s results might be linked to the impossibility of drawing the priming stimuli from comparable databases. Choosing appropriate and comparable stimuli was made even harder by a lack of description on words attributes (such as valence ratings) in the original study. To overcome this issues it is important to draw stimuli from published datasets when possible. Moreover, there should be a scientific effort into validating datasets across cultures and languages as it is been done for the ANEW (Montefinese et al., 2014; Redondo et al., 2007; Soares et al., 2012).

By no means I claim that the present research is perfect and would not benefit from methodological improvements. Methodological shortcomings have indeed been discussed in each experimental chapter. However, I think that factors that introduce variability in the data such as small effect sizes, different methodological choices and inherent cultural differences, make results difficult to replicate and might have partially contributed to the null results reported in this thesis.

To the best of my abilities, I attempted at approaching the work conducted in this thesis project with rigour and intellectual honesty. Explorative analyses were interpreted as such and bayesian factors provided additional information and validation of frequentist statistics. Hypothesis testing is after all an exercise of planned guessing on the basis of a-priori information and theoretical beliefs. There would be no need of hypothesis testing if research was not naturally intertwined with uncertainty. In simple terms, I believe that guessing it wrong is not less valuable that guessing it right, as long as the hypothesis are grounded in a solid theoretical framework. Nevertheless, I do believe that publication bias and low reproducibility in the field of psychophysiology and cognitive neuroscience may have contributed to the null results reported in this thesis.

5.4 Suggestions for further research

Directions for future research for the specific improvement of each experiment were discussed in each experimental chapter. Methods for eye-blink correction may help in reducing the variability in the data of chapter 2 and time-frequency analysis may provide additional information on whether the psSME is of attentional nature. Multivariate pattern analyses could be used to decode the cognitive process involved in the psSME. Furthermore, optimizing the attention task as suggested in the discussion of chapter 2 would indeed allow us to properly test the original hypotheses.

Although weak, the results of chapter 2 seemed to point towards semantic processes being responsible for the psSME. However, processing maths is thought to rely on visuospatial skills. Therefore, it would be interesting whether psSMEs can be detected with visuospatial stimuli. For example, arrays of objects that vary in colour or position could be presented and participants would have to later recollect what array was previously presented amongst some new ones. If the psSME can be detected with visuospatial material, then high maths-anxious (HMAs) and low maths-anxious (LMAs) could be compared to assess whether they differ in VSWM encoding. If that was the case, it would provide an insight into cognitive differences between groups, regardless of anxious arousal. However, it is possible that the two groups would not differ in a context where anxiety is not elicited. Hence, it would be interesting to integrate the NPU-threat test with such paradigm to assess difference in susceptibility to stress during VSWM encoding. Because combining EEG with shock administration would probably not fall short of methodological challenges, shocks could be replaced with other threatening stimuli not involving electricity (Schmitz and Grillon, 2012). Finally, paradigm assessing the psSME with vusuospatial material could be combined with maths tasks to assess the effect of anxious responding when maths is explicitly required to perform a task.

Regarding the research questions addressed in chapter 3, increasing set size in the experiment or employing several set sizes would be the first step to take in order to assess the effect of anxiety over the allocation of flexible resources. If again there was no effect of anxiety on precision of recall it could be suggested that anxiety does not impact how attentive resources deal with noise during visuospatial WM maintenance. It may be that visuospatial WM is less disrupted by anxiety compared to other subsystems. Alternatively, it may be that the attentional resources engaged in WM maintenance are dissociable from the executive functions impacted by anxiety as theorized by the available models (for instance the ACT). Different maths-anxious groups could be compared. It would be possible to test whether HMAs have decreased precision of recall compared to LMAs or whether thei precision of recall is more disrupted by increasing set sizes. This would give an insight into whether HMAs are more susceptible to noise generated by internal representations. Similarly, a delayed-estimation task could be combined with a maths task. This would allow to assess whether maths task increases anxious arousal in HMAs and whether that has a detrimental effect over maintenance in VSWM.

Regarding chapter 4, the affective priming task paired with the arithmetic verification task needs replication or at the very least conclusive evidence for the unsuitability of such task. Optimising the choice of priming words as well as selecting participants with extreme values at the AMAS would be the first step to specifically improve the work already conducted in this thesis. On a more general level, the importance of physiological measures of MA should still be kept under the focus of attention of psychophysiology. What is needed at this stage is determining reliable measures of anxiety that could be then employed to assess anxiety in specific scenarios. Measures of HRV need to be investigated further as HR data have the advantage of being easy to collect in real life situations. For example, the growing use of sport watches with integrated HR monitor make HR a very appealing measure for testing during real maths exams in school. HR is an easily acquirable measure of MA that is suited for ecologically valid testing.

5.5 Conclusions

In summary, the present thesis adopted physiological measures to investigate the relationship between anxiety and WM. Furthermore, the importance of WM for maths processing and the sensitivity of physiological measures to both anxious responses and executive processes make these measures appealing for advancing our understanding of MA.

The experimental work did not output the expected results. First, the prestimulus memory effect was replicated although the replication cannot be interpreted as conclusive. In addition, I was not able to convincingly resolve the debate over the nature of such effect. Second, it has emerged that there is no effect of anxiety of the flexible allocation of resources in WM, at least with small set sizes. Third, the affective task paired with the verification task did not replicate the original behavioural findings. Hence, not surprisingly little was found in the physiological measures as well. While methodological shortcomings have been discussed in the thesis, low reproducibility in the field of physiology and cognitive neuroscience might have played a role in the final outcome of the preset research project.

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